Immersing Architecture:

The Futures of Undersea Development

Chad Henderson
May 2009

Submitted towards the fulfillment of the requirements for the Doctor of Architecture Degree

School of Architecture

University of Hawaii

Doctorate Project Committee
David Rockwood, Chairperson
Jim Dator
John Wiltshire

TABLE OF CONTENTS

Prologue

Throughout time, mankind has fulfilled an instinctual obligation to explore the environment in which he finds himself. Scaling mountains, exploring caves, and surveying valleys appear to be a visceral act of the human condition. But until recent history, the ocean realm was precluded from these investigations. The thick medium caused eyes to burn and respiration to cease. The rippled surface was an impenetrable barrier to the mysteries below, passable only by clumsily splashing across the surface. Because of this, folklore engulfed imaginations and told of monsters that inhabit the curious depths beyond our sight.

"With the rise of civilization, the search for new wealth and the elevation of national pride drove explorers to risk their lives and benefactors to empty their coffers in the quest for discovery. All of these factors — survival, inspiration, wealth, and national pride — provide the fundamental justification for proposing the most ambitious chapter ever in the history of human discovery of this planet: the exploration of Earth's oceans."[1]

Hindered only by the limits of curiosity, explorers have delved into the murky blackness to better understand the world in which we live. However, a human's ability to explore the depths has been invariably linked with the development of technology. Every day, entrepreneurs invent new devices that allow them to further trespass on this area that humans have never tread. It is for this reason that ocean exploration is more feasible today, than it has ever been in the past.

In my own experience, I have found that there is an innate fascination with traveling beneath the waves that is difficult to describe. Jacques Cousteau recounts his first experience:

"One Sunday morning in 1936 at Le Mourillon, near Toulon, I waded into the Mediterranean and looked into it through Fernez goggles. I was a regular Navy gunner, a good swimmer interested only in perfecting my crawl style. The sea was merely a salty obstacle that burned my eyes. I was astounded by what I saw in the shallow shingle at LeMourillon, rocks covered with green, brown and silver forests of algae and fishes unknown to me, swimming in crystalline water. Standing up to breathe I saw a trolley car, people, electric-light poles. I put my eyes under again and civilization vanished with one last bow. I was in a jungle never seen by those on those who floated in the opaque roof.

[1] U.S. Deparment of Commerce, *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*," President's Panel for Ocean Exploration, 2001

Sometimes we are lucky enough to know that our lives have been changed, to discard the old, embrace the new, and run headlong down an immutable course. It happened to me at Le Mourillon on that summer's day, when my eyes were opened to the sea."[2]

I feel that men like Cousteau and I have been irreparably changed by our experiences in the sea. Likewise, these experiences are so deeply moving in our own psyche that we can correlate our sharing of this submerged world with that of a service to humanity. Though it may be blasphemous to compare my trifling undersea experience to that of Cousteau or to liken it with more humanitarian efforts, I find the same excitement and fullness when I am permitted to share my love for the sea. It is this obligation, to share the undersea environment, which drives me to conduct research on the future exploration and colonization of the unexplored depths of our planet.

[2] Jacques-Yves Cousteau and Frederic Dumas, *The Silent World* (London: H.Hamilton, 1953), 5

1 INTRODUCTION

In recent years, I have been inspired by entrepreneurs who have endeavored to develop boutique hotels at the bottom of the sea. These remarkable projects of Fiji and Dubai foster the thoughts of what the future may hold for mankind and its involvement in the ocean realm. With climate change, energy issues, and ever increasing densities in recent discussions, mankind must seek to better understand and utilize the medium that covers two-thirds of this planet.

It is from these ideas that I have decided to study the future of buildings and their role beneath the waves. By examining the benefits of a life intertwined with the sea, I believe mankind can develop a whole new facet of the human experience and introduce a unique model into architectural development.

In this document, I hope to propose that life underwater is not only feasible, but desirable; that building undersea can formulate a new paradigm in the discipline of architecture, and that life offshore can become a contributive appendage to a city's function.

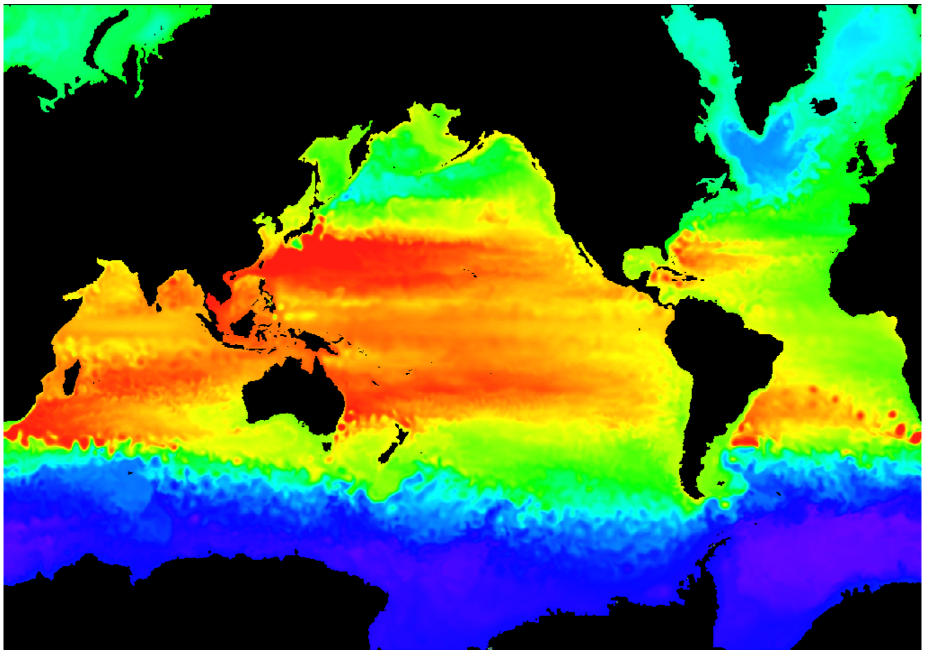
I intend to orchestrate these ideas in the context of a visionary architecture framework. Visionary architecture serves to propose ideas and discussions for future architectural investigations. It provides the "what if?" proposal to inspire further works. Following the lead of speculative architects such as Antonio Sant'Elia and groups like Archigram, I aim to propose new contingencies of our architectural futures. These responses will be based on preferred futures, modeled from considerations of sea level rise and other current projections. Though hypothetical, these future scenarios will help to discuss one possible future in which a new architectural paradigm is required. Like other visionary architectural proposals, these findings will be largely speculative in nature. The hope is that they will demonstrate the theories outlined, as well as, inspire others to further develop these ideas in their own works.

2 DEVELOP UNDERWATER?

In any discussion concerning an alteration to the accepted and established patterns of life one must ask "why?" If the environment is stable, there is enough room, and energy is abundant, why create a new model? The truth is that aside from exploration, adventure, and novelty, some may not choose an aquatic life over one based on land. However, plausible scenarios exist where the environment is not so stable, where population densities are growing and energy issues are a grave concern.

In these scenarios, mankind must expand the boundaries of life and knowledge; to seek avenues of augmenting the human experience and adapting their cities to life on this planet. In an environment that has been consistently labeled as "changing" humanity should be looking for ways to accommodate this change. Throughout time, all species' survival has been linked to their ability to adapt and evolve. Our species is no exception. Therefore, in parallel to looking for ways to diminish imbalances in the environment, we should be examining ways of adapting to a new era of human existence.

2.1 Climate Change



0-1 Thermal map of the world

It is possible that undersea habitats may offer a few mitigating solutions to global climate changes. Obviously, one need not be concerned with sea level rise if one is already underwater or prepared to be submerged. An opportunity is created for homes that could be constructed to accommodate changing sea levels. Rather than deny sea level rise or continue creating sacrificial structures, buildings could accept a rising ocean. As the spaces immerse, new and exciting qualities emerge. This principle alone can transform a catastrophe into a beautiful new paradigm of architecture.

In addition, undersea installations exist in one of the more stable environments on this planet. Temperature changes undersea are not as radical as the surface. Despite radical fluctuations in seasonal temperatures in the atmosphere, the sea only warms and cools a few degrees. This fluctuation becomes more minuscule, the deeper one travels. These stable temperatures may offer a more suitable environment for controlling atmospheric comfort in residences.

2.1-2 Levees overtopping, September 2008

Another growing concern is that the severity of storms, whether associated with climate change or not, will continue to ravage coastlines. Floods, hurricanes, storm surges, tsunamis, and other inclimate conditions are catastrophic when they encounter coastal areas. Undersea installations may offer a more stable environment during these events. They are relatively unaffected by flooding, wind and other atmospheric instabilities.

A recurring speculation of global climate change is that the sea level may one day rise to reclaim land once used for living. This decrease in usable land creates concern for loss of infrastructure, population relocation, and housing shortages. Clusters of undersea residences may provide relief for some of these scenarios. By maintaining the use of previously dry land, these areas sustain utility for the city.

Undersea installations could offer housing, entertainment, and other utilities to maintain the productivity of coastal sites to urban settings.

There exists an unimaginable amount of energy stored in the ocean. This is found in solar, wind, wave and tidal potential. By existing in the waters that harbor these energies, undersea installations could easily become the powerhouse of an small community. Technologies like ocean thermal energy conversion, tidal turbines and wind turbines could culminate in delivering a significant surplus of power to the shore. By providing clean energy, as well as, housing the workforce needed to maintain the complex equipment.

2.2 The Splendor of Submergence

2.1-1 Hawaiian Green Sea Turtle

The underwater realm has long been associated with calming effects and a sense of wonder. The calming blue hues of the deep permit visitors to abandon their worries on the surface. The near absence of sound allows the mind to relax and focus. And the weightless, gliding motions of the creatures that surround are mesmerizing. Alternatively, some find their submerged experiences to be thrilling. Despite safeguards, some capture a feeling of risk, as though they were trespassing into a medium that they were not meant to go. Others channel their inner explorer, emulating pioneers like Jacques Cousteau, on expeditions into an environment that we still know very little about. Though complex, many would describe these conditions, even when visiting aquariums or scuba diving. Therefore, it is not absurd to think that some individuals may hope to capture some of these feelings of calm and wonder into their homes.

With underwater environments developing around the world, one wonders what drives these endeavors. It would be far more economical, sustainable and prudent to build on dry land, but developers still choose coastal locations for their most grandiose projects. Even more so, waterborne architecture pushes the boundaries of engineering and pocketbooks. Why is mankind fascinated with the ocean environment? Why risk so much for what may be considered a trifling novelty? The answers to these questions do not come easily, but one thing is certain. Mankind's existence and fantasies have, and will continue to be, inescapably intertwined with the sea.

2.3 The Human Experience

There are an infinite number of events that occur in one's lifetime that compile into what I label "the human experience." From birth, each new experience enriches the quality of our lives and reveals another complex relationship embodied in the system in which we live. Opportunities to expand the breadth of these experiences and enrich our understanding are momentous. I feel that man is on the cusp of a great expansion into the understanding of the world in which we live. By opening the sea to mankind and allowing them to experience its grandeur, we empower humanity to discover the last unexplored realm on earth; thus revealing another facet of the human experience.

2.3-1 Freediving Ascent

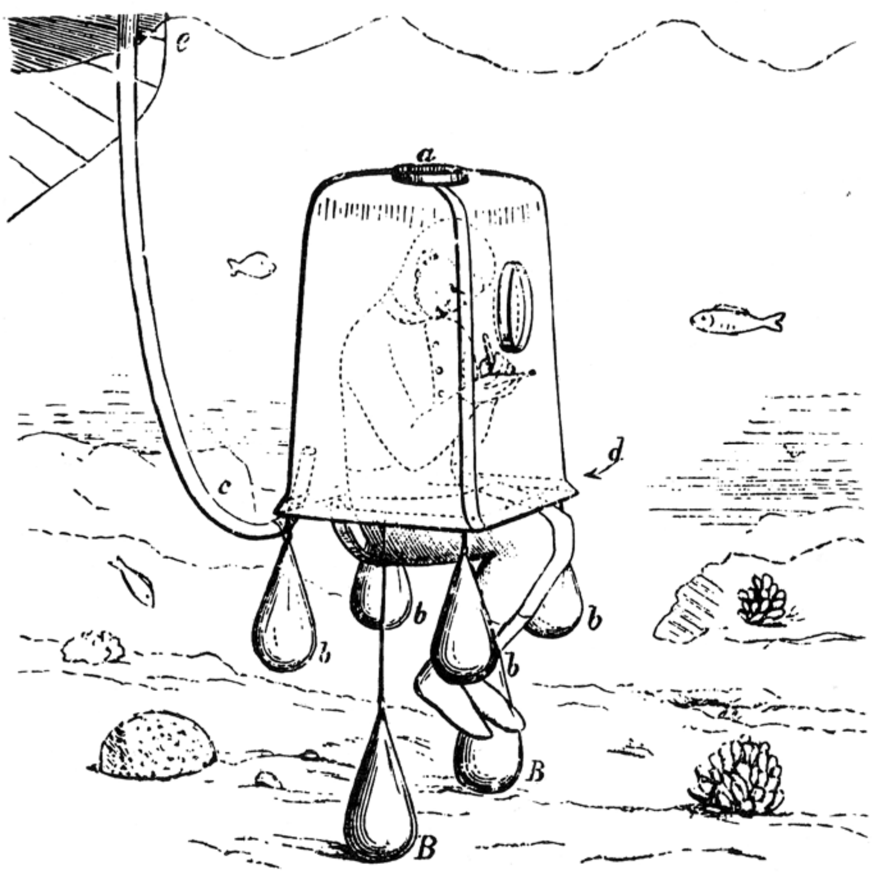
In discussing architecture, one often draws parallels to known experiences to convey an unconventional idea. When exploring the concept of underwater architecture, discussions often gravitate towards science fiction and aquarium experiences to describe the spaces envisioned. I feel that we do not have to search so far to understand the meaning of an undersea space. The relationships that exist between man and the sea are far more primal than science fiction writers would have us believe.

My belief is that immersing our homes in an undersea environment is more like regressing into the womb. Unlike the surface of the ocean or the outside world, our life in undersea habitats is sheltered and secure. All provisions to sustain ourselves are provided through an umbilical. Like a mother, the deep sea envelopes undersea structures and protects them from the harshness of the surface. We are segregated from an outside environment.

We are in a fetal stage of understanding the ocean realm. Only after allowing ourselves to develop our understanding in a protected state, will we be afforded to opportunity to thrive in the sea. Despite the prerequisite of technology; the steel, the acrylic, and the air supplied so that we may survive, I maintain the argument that living in the ocean is not an unnatural act. We developed all our human traits while floating in a lilliputian sea. Returning to the undersea realm is like returning to the aqueous solution of our genesis. The shell of the habitat, in which we reside, protects us from an outside world. This shell, like a mother's body will protects us while we develop; while we mature into creatures that are prepared to occupy the environment that surrounds us. These endeavors into undersea existence are merely an echo of the circumstances that brought us into this world.

3 HABITATS UNDERWATER

In order to better discuss the future of habitation on the seafloor, it is prudent to first examine its history. The following is an exploration of pioneering underwater habitats and the lessons learned from them.

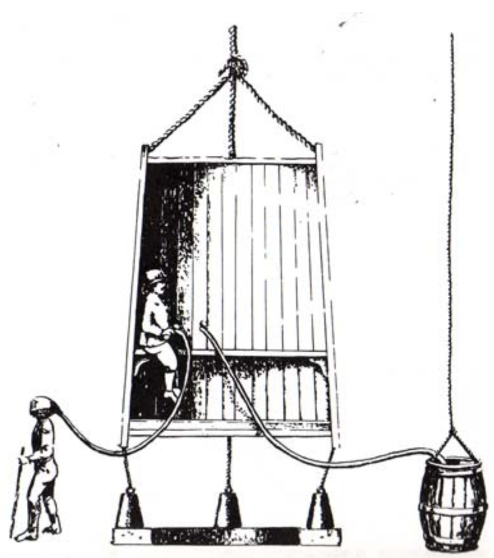


2.3-1 SIMPLE DIVING BELL

3.1 THE BEGINNING

From as early as Alexander the Great, man has sought to reside beneath the waves. Legend states that Alexander commissioned the creation of a glass barrel, large enough to fit a man. With the aid of chains, the conqueror was lowered into the water. Upon returning, he told of a fish so big, that it took three days to swim past him and moved with the speed of lightning.[3] Unfortunately, Alexander's historic barrel, as well as his fish story, is only legend. However, some of the first diving bell habitats were exhibited in Greece as early as 1538.[4]

Diving Bells were bell-shaped devices that, when lowered into the water, trapped air inside. The principle of bell diving may be demonstrated by simply plunging a glass upside down in a bowl of water. Only the amount of water needed to equalize the pressure in the glass will enter. The rest of the glass, and its contents, will remain dry. These simple contraptions allowed divers to use the trapped air for breathing.



3.1-1 EARLY DIVING BELL

[3]Frank Ross Jr., Undersea Vehicles and Habitats:The Peaceful Uses of the Ocean (New York: Thomas Y. Crowell, 1970) , 4
[4] *Ibid.*, 6,7

Transportable bells permitted divers to make short excursions from underwater stations, thus creating the first underwater habitats.

Although a myriad of technological advances were to be made in the years to follow, man was still plagued with short visits to the sea floor. This was due to the human body's increased absorption of nitrogen at the greater pressures of depth. To limit this absorption to a safe rate, divers could only remain submerged for a specific period of time. If this time was exceeded, or if the diver ascended too quickly, they could risk decompression sickness, air embolism, or even death. Dives to greater depths required lengthy stays in a decompression chamber. This chamber allowed divers to slowly return to the pressures of the surface and expel the nitrogen in their system at a safe rate.

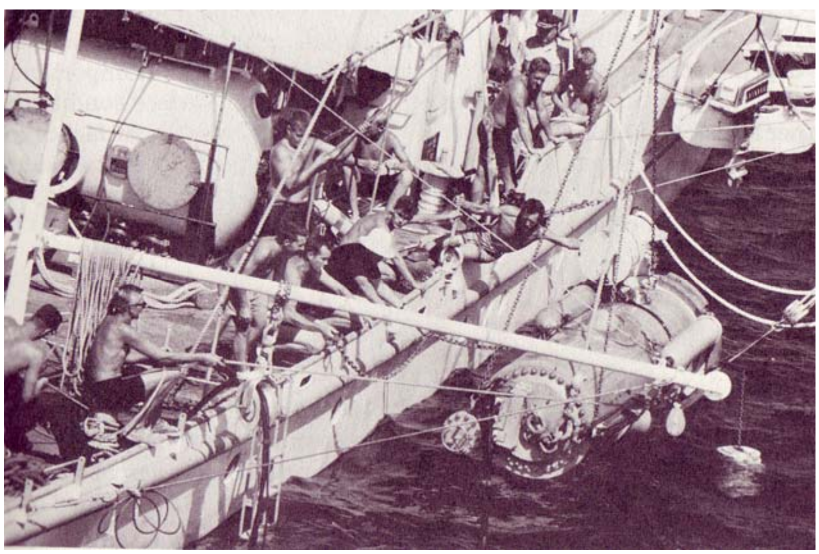
In 1957, Dr. George F. Bond would conduct a series of experiments that would challenge these limiting bottom times. The "Genesis" experiments (1957-1963) proposed the idea of divers enjoying limitless bottom time through saturation diving.[5] Saturation diving is conducted under the idea that once the body has absorbed gasses to form an equilibrium with the surrounding pressure, it will absorb no more gas.[6] This is similar to the idea that once a sponge has soaked up all the liquid it can, it cannot soak up any more, regardless of the presence of more liquid. This idea is revolutionary in habitat diving because once a diver has spent about 24-36 hours underwater, the body has equalized with the surrounding pressure and will not absorb any more gasses.[7] This means that after about one day, additional days submerged do not add to the amount of time needed to decompress.[8] This was important because divers could now safely occupy the sea floor for multiple days, without adding to their decompression schedule.

---

[5] James W. Miller and Ian G. Koblick, *Living and Working in the Sea,* 1984, 16
[6] U.S. Department of the Navy. U.S. Navy Diving Manual. 1970, NAVSHIPS 0994-001-9010, 79-86
[7] James W. Miller and Ian G. Koblick, *Living and Working in the Sea* (New York:Van Nostrand Reinhold Company Inc. 1984), 15
[8] *Ibid.*

3.2 Early Tests

Operating on Dr. Bond's principles, the first modern attempt at a deep sea habitat was undertaken in 1962, by an inventor named Edwin Link.[9] Link was an underwater archeologist who was growing increasingly frustrated by the short bottom times allowed by conventional scuba diving. In 1956, he submitted to a committee of the Smithsonian Institution an outline of his goal "to put man in the sea, safely, deep and long enough to enable him to do useful work."[10] The culmination of this proposal would arrive 6 years later in a habitat called Man-In-The –Sea. Link's design was an aluminum cylinder of only 3 ft. by 11 ft. At this size, there was only room for one occupant. This cylinder was to be tethered to a support ship and lowered to its



3.2-1 Launching Man in the Sea I

operating depth of 200 ft. Although the test fell short of its 48 hour goal, the project did manage to stay submerged for 24 hours and 15 minutes, thus, making Robert Stenuit the world's first aquanaut.[11] Among the many lessons learned by Link and his team, one

[9] James W. Miller and Ian G. Koblick, Living and Working in the Sea (New York: Van Nostrand Reinhold Company 1984), 28.
[10] *Ibid*., 25.
[11] *Ibid.,* 28.

was that future habitats would have to be anchored to the sea floor to eliminate weather issues encountered with ship-tethered structures.

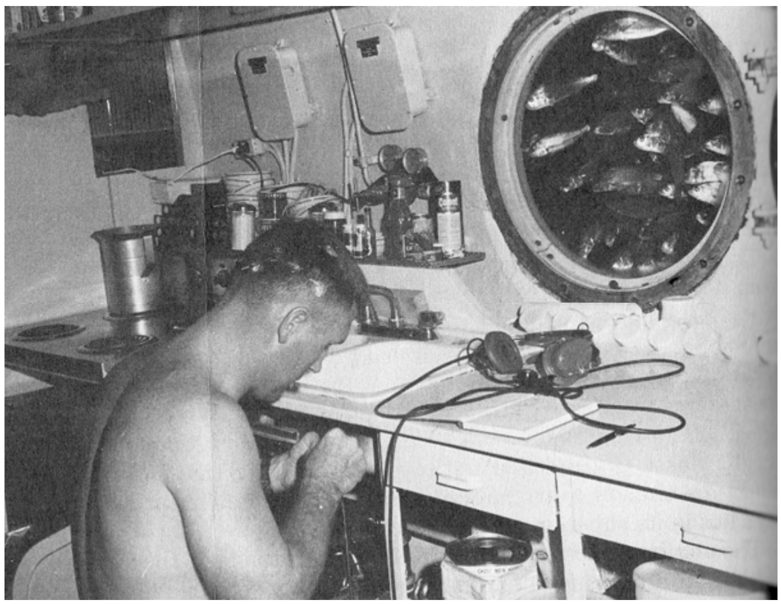
Only four days after the termination of the Man-In-The-Sea project, the Office Français de Recherchs Sous-Marines of France launched their Conshelf mission, under the supervision of Jacques-Yves Cousteau.[12] The first Conshelf cylinder was larger than Link's, measuring 8 ft. by 17 ft. It was oriented on its side and was anchored to the bottom, using pig iron and heavy chain. It supported two crewmen for a period for 7 days. Conshelf II followed only 9 months later and was able to support 5 aquanauts for 4 weeks. Both excursions proved the ability of men to remain submerged for extended periods and carry out tasks without risking physical injury.

In Later years, the U.S. Navy Tektite missions would develop additional breadth of expertise in this developing discipline. Like previous habitats, their missions were based upon the work of marine science. The distinction was that the observers were largely concerned with the psychological examination of groups in confined space. Their habitat was ideal for behavioral observation because subjects were completely removed from outside influences that may corrupt the experiments. The aquanaut's behaviors were recorded and analyzed to create selection criteria for future underwater habitats and "to obtain data applicable to problems of long duration space flight."[13] At the conclusion, researchers determined that "not only can individuals cope adequately with confinement and isolation, they can also perform work roles effectively in such a setting. "[14] These experiments displayed that neither the confined spaces of underwater habitats, nor the stress of submergence were significant forces to alter the psychological health of participants.

---

[12] *Ibid.,* 30.
[13] Robert Helmreich, *The Tektite II Human Behavior Program: Human Reactions to Psychological Stress* (Springfield, VA: National Technical Information Service, 1971).
[14] *Ibid.*

The major success of these early habitats was that they provided man with a means of uninterrupted presence on the sea floor. This was a huge achievement for the marine sciences because they were now able to observe marine life without the need to surface. Long term experiments could be carried out that were not possible from submersibles or ship based operations. Additionally, missions could be carried out regardless of weather conditions on the surface. `



3.2-2 Observing Marine life in Sealab II

4 CURRENT ENDEAVORS

Today, the presence of underwater habitats around the world has dwindled. However, a few operations maintain the intrepid spirit of the projects that preceded them. They function to perpetuate man's education of the sea floor and hope to inspire others to foster the relationship between man and the sea.

3.2-1 AQUARIUS UNDERSEA LABORATORY

4.1 Aquarius

Although the primary goals of habitat operations were rooted in the Marine sciences, only one installation remains dedicated to that purpose. The last remaining sunken laboratory is the Aquarius Habitat off the Florida Keys. Deployed in its current location in 1992, the Aquarius lab has supported more than 90 missions and been the training bed for numerous aquanauts, marine scientists, and astronauts. [15] The habitat is still of great benefit to marine science due to the fact that it allows researchers to remain on the sea floor for extended observations. Researchers relate that:

> "A 10–day Aquarius mission would take more than 60 days if conducted using surface–based technology, and few scientists have the time to spend months in the field, when a 10–day Aquarius mission can be used to accomplish the same goals. This assumes that the work could even be conducted from the surface, which many times is not the case because Aquarius provides unique laboratory capabilities."[16]

Though the operating costs are near $10,000 per dive day,[17] the laboratory finds value in allowing researchers to observe the sea floor for longer periods. Traditional SCUBA diving methods would take much longer to equal the habitat's observation time. Therefore, SCUBA research, though less expensive per day, takes longer and may reach a higher cost. Shorter mission times may control costs and allow researchers to spend less time in the field and more time on analysis.

One of the more widely popularized uses of the Aquarius Habitat is as a test bed for space station equipment and astronaut training. NASA employs Aquarius by

---

[15] Potts, Thomas, "NOAA's Aquarius Undersea Laboratory," University of North Carolina Wilmington, http://www.uncw.edu/aquarius/index.html (accessed September 9, 2008)
[16] Potts, Thomas, "NOAA's Aquarius Undersea Laboratory," University of North Carolina Wilmington, http://www.uncw.edu/aquarius/index.html (accessed September 9, 2008)
[17] *Ibid.*

training astronauts for prolonged isolation at the international space station. They have fostered this technique since 1965, when Scott Carpenter of the Mercury program spent 30 days in Sealab II off the coast of California.[18] Many devices and procedures are tested on these underwater sites before making their way to the international space station. Bill Todd, the NASA Undersea Research Team project leader said that "no environment on Earth can capture the essence and isolation of space better than the ocean … it's as close as you will get to actually living and working in space."[19]

4.2 Biosub

Elsewhere in the world, marine habitats are being used to pursue ideas of sustainable living. Lloyd Godson of Australia lived in his submerged, homemade habitat for 12 days. His primary interest was to explore closed ecosystems. Dennis Chamberland, former NASA bioengineer and research aquanaut stated that:

> "the picnic approach of packing everything and bringing your waste back home is far too expensive for long term space and sea settlement. Explorers have to focus on bioregenerative systems if they plan to move into these frontiers." [20]

Godson recognized this need and applied for a grant from an Australian Geographic "Live Your Dream" contest in 2007. From this, he was awarded $50,000 to build what he called the "Biosub."

4.2-1 The Biosub

Though the Biosub experiment was not ground breaking in its duration, the activities conducted while in the vessel were significant. As a marine biologist, Godson

[18] Frank Morring Jr., *Deep Space* (Aviation Week & Space Technology; Vol 161, Issue 2, 07/12/2004) 32
[19] Tim Friend, *Astronauts train in NASA's deep space brine* (USA Today, 05/12/2002)
[20] Kathy Riley "Underwater Man Lives His Dream," *Australian Geographic*, July 2007, 32-37

wanted to learn more about living in a closed ecological system.[21] While underwater, his air supply was regenerated by a mechanism called a "Biocoil."[22] The Biocoil was a system that had been developed by a class from Cascade High School in Idaho, USA.[23] The students developed a system using Chlorella algae to replenish the air supply in the habitat. As part of its life cycle, the algae absorbed Godson's exhaled carbon dioxide and expelled oxygen. The Biocoil provided up to 10% of the habitat's oxygen. This reduced the need for carbon dioxide scrubbers and fresh air circulation. The remainder of his air supply was augmented by scuba cylinders and compressors.[24] By pedaling a bicycle, Godson generated electricity which provided power for his laptop and the light that the Biocoil needed to survive. The bicycle also rotated a small pump which circulated the algae in the system. Godson reportedly snacked on the high-protein Chlorella to supplement his food supply.[25]

Though this experiment was not a fully closed ecological system, it provided valuable data for future endeavors. The hope is that man may find a way to reproduce the balances found on earth in a smaller, transplantable habitat. These types of scenarios may one day lead to man's permanent subsistence on the sea floor, or even space.

4.3 Red Sea Star

In more recent installations, engineers and designers have proposed structures that can be easily accessed by the public. These habitats are open to the atmosphere above, therefore operating at the same pressures as the surface. This allows visitors to

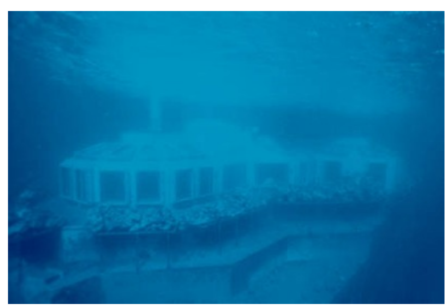
---

[21] *Ibid.*
[22] *Ibid.*
[23] *Ibid.*
[24] *Ibid.*
[25] Fred Koschmann, "The Aquanaut" *Popular Science,* September 2007, 42

arrive and depart without the need for SCUBA gear or decompression. Though this creates a greater engineering challenge in combating the pressures of depth, the benefit far outweighs it.

Thus far, Restaurants have been the most successful application of this technology. Patrons have found a great deal of novelty in dining on the sea floor. The first of these structures was installed in Eilat, Israel. The "Red Sea Star" restaurant is situated about 100 feet offshore in the Red Sea. The structure consists of three levels that are accessed from shore by a small bridge. The entrance level is about 12 meters above the water and contains a coffee bar, souvenir shop, and the restaurant's kitchen. Directly above this, there is a bar and dance floor. Finally, after an elevator ride down, you encounter the restaurant itself. This is situated about 20 feet underwater, surrounded by a cultivated coral reef.

The dining area is comprised of several metal sections welded together. The restaurant's website describes the completed plan as "star-shaped." However, most would feel that it more closely represents a crucifix. Either way, the layout allows for most seats to be situated next to a window. There are 62 windows in all, which account for 12 of the structure's 110 ton weight. The acrylic windows are 8.5-13.5 cm thick, depending on their size. To protect these fragile windows, a company in Japan placed a special layer of glass on the inside and outside. This prevents both guests and maintenance divers from scratching them.



4.3-1 Restaurant Exterior

The large interior of the restaurant was designed by the project designer, Sefi Kiryaty. She masked the harsh metallic structure with warm hues and ocean-inspired fixtures. She related that, “the amount of blue light coming through the windows posed a big problem. People looked blue and sick. So did the food.” As a result, she combated the cool blue with warm colors and softer edges of red and orange.[26] To reinforce the feeling of submergence, the light fixtures were inspired by jellyfish and the floor was finished with an epoxied layer of sand.

4.3-2 Restaurant Interior

[26] Edie Cohen, “Under the Sea,” *Interior Design*. July, 1999 142-147

4.4 ITHAA

In the Maldives, another undersea restaurant was installed in April, 2005.[27] The Ithaa restaurant was placed in a coral lagoon off the Hilton resort on Rangali Island. Patrons of this unique restaurant enjoy cocktails at the surface before being escorted down a spiral staircase, to the dining section below. Once inside, They are seated at one of only 14 seats available and enjoy a 220 degree view of the sea around them. The structure is located only 1 meter underwater at low tide.

4.4-1 VIEW INSIDE ITHAA

Only the diners are below, cooking and other services are provided from the surface portion of the operation. The Ithaa Restaurant, which means "pearl" in the Maldivian language of Divehi, claims to be the world's first "aquarium-style undersea restaurant in the world."[28] The structure measures 9 meters long and 5 meters wide. The acrylic section is comprised of three 125mm thick arches that are 3 meters wide

[27]Hilton International, "The Story of the First Aquarium-Style Undersea Restaurant in the World…" Hospitality Net, April 19, 2005, under "Industry News," www.hospitalitynet.org/file/152001986.pdf (accessed September 18, 2008)
[28]*Ibid.*

each. These arches are the widest yet constructed in the underwater world.[29] These arches were sealed together with silicone sealant at its assembly location in Singapore. Once the 175 ton vessel was assembled, it made a 16 day journey to the Maldives. There, 85 tons of sand were added for ballast and the restaurant was sunken onto piles. These piles were the selected method of connection to the seafloor due to their minimal impact on the existing reef.

The habitat takes a great deal of care in the safety of its guests. All access areas are 3 hour fire rated and sprinklered. Air conditioning was designed by Jackson Engineering of New Zealand to provide 3 air exchanges per hour and maintain a humidity level of 60%. Zinc anodes and a special marine paint protect the steel sections of the habitat from corrosion.

4.4-2 Ithaa Being Lowered into the Water

In 2004, the structure was tested when a tsunami struck the Maldives. Because it was submerged, the structure suffered no ill effects. The major concern was that the peak of the wave may allow water to enter at the top of the staircase. As it turned out, the water only reached 300mm below this critical level.[30] Despite its resilience, the expected lifespan of the installation is estimated to be around 20 years.

---

[29] *Ibid.*

[30] M.J. Murphy Ltd., “Underwater Restaurants: “Ithaa” (Pearl) – The Hilton Maldives Undersea Restaurant,” M.J. Murphy Ltd., http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx (accessed September 18, 2008)

4.5 HUVAFEN FUSHI

Also in the Maldives, a new model of spa has been developed. Huvafen Fushi is a new spa treatment center that administers treatments under water. Two, double occupancy, treatment rooms are located just beneath the water at the resort. Just above, 6 more treatment rooms exists with glass floors. Even the treatment tables and the treatments themselves have been custom designed to allow guests to watch the tranquil waters outside. The entire subsea portion of the structure is constructed from 5 inch thick cast resin. It took 12 months to construct and, according to their advertising, "exceeds the specifications demanded by the American Standards Authority."[31]

4.5-1 HUVAFEN FUSHI SPA

The operators assert that: "The philosophy behind Aquum Spa is the simple concept that water is the equilibrium and elixir of life - restorative, calming, balancing and renewing vitality. It is about living authentic to nature. With a

4.5-2 UNDERWATER TREATMENT ROOM

[31] Hotel Online, "Research and Engineering Creates an Underwater Spa at Huvafen Fushi Resort in the Maldives," Hotel Online, September 28, 2004, under "Special Report," http://www.hotel-online.com/News/PR2004_3rd/Sept04_Huvafen.html (accessed September 19, 2008).

resurgence in the popularity of water treatments, Aquum Spa's underwater treatment rooms take the water experience to a completely new level, creating a rejuvenating encounter with water, in a way that no other spa has done in the world."[32]

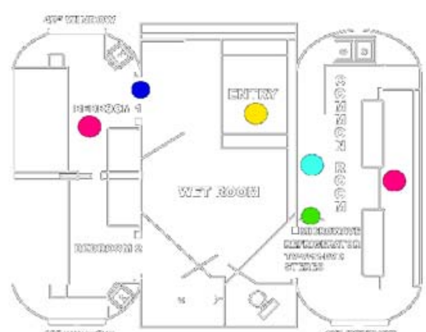
Ultimately, these hospitality installations may exhibit more about the human condition than saturation diving experiments have. Though the saturation missions were revolutionary, these projects show that not only can people inhabit the sea floor; they find it intriguing, healing and desirable. The success of these businesses show that people are fascinated enough with these experiences, that they are willing to pay a premium fee.

4.5-3 Lighting Effects Underwater

4.6 Jules' Undersea Lodge

In the next revolution of designs, entrepreneurs have created hotel rooms underwater, complete with television, room service and a view. These offer extended stays for hotel guests, without the need for decompression.

Off the coast of Florida, Jules' Undersea Lodge re-tasked the former "La Chalupa" laboratory for this purpose. Formerly residing off of Puerto Rico, the



4.6-1 Habitat Map

[32] *Ibid.*

habitat now rests in about 30 feet of water in the Emerald Lagoon in Key Largo Florida. Lodge visitors must scuba dive to their room's entrance. Located 21 feet underwater, the habitat's wet room allows divers to enter via the moon pool, remove their gear, shower, and join the rest of the occupants in the common area. There are two bedrooms in the structure. Both rooms contain beds, a sink and a 42 inch window. In the common area, there is a small kitchen, a television, books and a stereo for guests to enjoy. Food is delivered via waterproof containers and prepared by a personal "mer-chef." Even items such as pizzas and wedding cakes can be delivered upon request.

Certified divers may enjoy unlimited diving with fresh scuba cylinders delivered regularly. The operators assert that decompression tables do not include the shallow depths of the lagoon in their calculations. Therefore, extended stays are not harmful and decompression is unnecessary.[33] Despite this, visitors are still able to qualify for habitat diving certifications and aquanaut status.

For safety, the lodge provides communications, power, water and fresh air through an umbilical cable which is connected to a control center. The control center is manned 24 hours a day to monitor the systems and provide any services that the occupants may request. In addition, the habitat itself has independent support systems, as well as,

4.6-2 Lodge Dining Hall

[33] Jules' Undersea Lodge, "Jules' Undersea Lodge: Media Information," http://www.jul.com/mediainfo.html (accessed September 19, 2008).

redundant backup systems.[34]

The safety and success of Jules' Undersea Lodge has undoubtedly inspired numerous entrepreneurs to construct their own undersea vision. The internet is riddled with ideas for the next generation of undersea living. Most feel that ambient pressure habitats, like Jules' Undersea Lodge, are outdated. Ian Koblick, renowned underwater habitat specialist and author stated that, "I think there is a very limited number of people willing to take their clothes off and hold their breath to get to their room."[35] The popular idea is that future habitats will be pressurized to one atmosphere and allow occupants to come and go as they please, without ever getting wet.

---

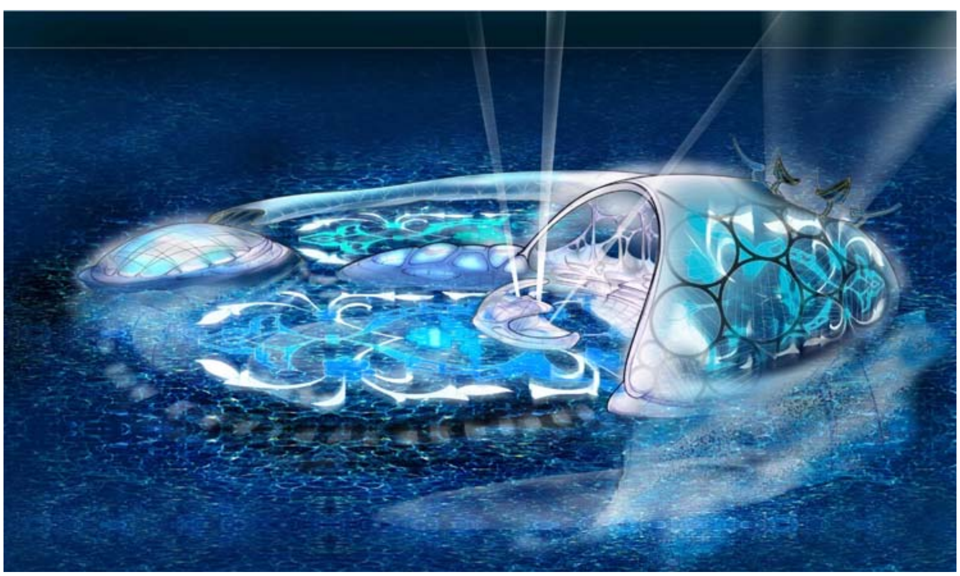
[34] *Ibid.*
[35] Behar, Michael. "1,200 SQUARE FEET UNDER THE SEA." *Popular Science* 270, no. 1 (January 2007): 64-68.

5

6 Immersed in Opportunity

The prospect of life in the sea has proven to be an attractive offer for many people. An opportunity to survey the unexplored depths of our mysterious oceans is an experience that many long to have. Adventurers and eco-tourists have been clamoring for these sparsely distributed encounters and have been found willing to pay a premium for what they can get.

As with many other emerging industries, enterprising individuals are seeking to capitalize on this deficiency in underwater exploits. Currently, two such entrepreneurs are racing to fill this void with the world's first underwater resorts. Bruce Jones of U.S. Submarines and Joachim Hauser of Crescent Hydropolis Resorts PLC are competing to create single atmosphere habitats, where visitors may conduct unencumbered stays at depth without training or worry.



4.6-1 Hydropolis

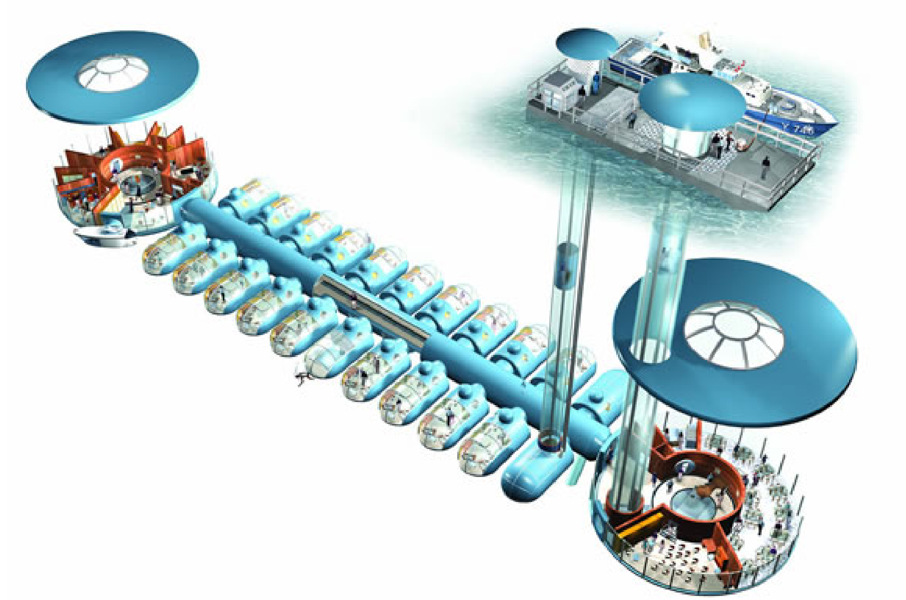
6.1 Poseidon

Bruce Jones has been developing submarines for wealthy eccentrics since his firm U.S. Submarines first opened in 1993. Having developed some of the world's only private, deep diving submersibles, Jones has turned his attention to more permanent expeditions into the underwater world.

6.1-1 Cabin Interior

In the race to open the world's first underwater resort, it appears that Bruce Jones and his Poseidon resort are in the lead. Scheduled to open after September 2010, his installation has been designed to be placed off of "Mystery Island" in Fiji. Like his competition in Dubai, Jones' installation has a land-based component and an underwater element. Guests enjoying a weeklong stay will spend 5 nights on the beach and 2 nights under the sea. The undersea portion will consist of 24 individual rooms, measuring about 550 sqft. each. A luxurious 1,200 sqft. "nautilus" suite will also be available for an estimated $15,000 per night.[36] Other undersea amenities will include a reception lounge, restaurant, bar, library, spa, conference room, and even a wedding chapel.

[36] Behar, Michael. "1,200 SQUARE FEET UNDER THE SEA." *Popular Science* 270, no. 1 (January 2007): 64-68.



6.1-2 COMPOUND LAYOUT

As with any sea-born structure, cost is a daunting obstacle. Fortunately, Jones has employed some ingenious techniques to tame the price of construction. First, he has chosen to construct each room as a separate vessel. The hotel rooms will be individually sealed against pressure, independent of the main structure. At the site, a unifying "spine" will be installed first, and then each room will dock to it. The spine will serve as circulation and provide utilities for the units. This technique will allow the units to be built and serviced individually. If one unit falls out of repair, it may be removed and evaluated on the surface, where complexity and construction costs are greatly reduced. Additionally, it becomes possible to construct the entire unit on land. Only the docking procedure is carried out on-site, where construction costs are their greatest. The plan is to assemble the units in Oregon and float them on a barge to their final destination in Fiji. In his first iteration of this design, Jones calculated that he would reduce the cost of construction from $3,700 per sqft. to $1,800 per sqft. by employing this modular approach.[37]

Another hurdle to overcome was the outrageous cost of manufacturing the large acrylic sections that will make up the units' impressive domed roof. For optimum

[37] Gengler, Amanda. "Sleep With the Fishes." *FSB: Fortune Small Business* 14, no. 10 (December 2004): 67-70.

visibility, each room's structure is comprised of 70% acrylic and 30% steel. This is almost precisely inverse form the ratio in the submarines the company usually builds.[38] The level of quality that they required for these critical parts was not available at a price that was permissible for the budget. Therefore, to create these acrylic pieces, the U.S. Submarines Company was tasked with establishing their own acrylic manufacturing facility.

Though Jones feels that the construction of an underwater hotel is less complex than the submarines he usually builds, there are many more tasks to carry out before the 2010 opening. However, with his modular approach, U.S. Submarines possesses one of the closest possibilities for underwater habitation for the masses.

6.2 Hydropolis

On the other side of the world, a German architect is attempting to move forward on his plans for the largest underwater resort in the world. Joachim Hauser, Executive Chairman of the Board for Crescent Hydropolis Resorts PLC, hopes that his design will make a stunning addition to the already ostentatious city of Dubai.

6.2-1 The Hydropolis Resort

Neighbored by some of the most ambitious endeavors in construction, Hauser hopes that the $500 million dollar project will be the start of many things to come:

[38] *Ibid.*

"For years we have followed the trends towards greater interest in water and the sea, and the idea of settling under water has been around since antiquity. People associate certain states of mind with water – such as relaxation, tranquility and harmony. So it is a logical step to settle under water. But I do not see this as just the construction of a hotel; it is a first step towards building on a larger scale under the sea. It is the beginning of a new architectural era."[39]

Hauser's idea of building on a larger scale than his already gargantuan project is a bit pretentious. His project will be built over a total area of 107,700 square meters and operate 220-300 underwater suites.[40]

Most sources indicate that the Hydropolis project has not progressed much in the past few years. It was scheduled for a 2006 opening, which has now been delayed. Despite this, the design process has continued. Even the psychological aspects of the design have been considered. Mitigating factors include biodynamic lights to create artificial night and day and skylights that penetrate the surface to bring in natural light. Hauser insists that, "We have designed the architecture and interior in such a way that no one will develop any anxieties."[41]

There have been no indications that the designs have become anything more than ideas. Hauser informs reporters that he is fully funded and will be beginning construction soon. However, the scale and absurdity of some of his design features may preclude him from a speedy completion. Of the more outlandish proposals are a system to produce artificial clouds for climate control and a missile defense system for warding off terrorists. Despite his bizarre propositions, the city of Dubai has continually

[39] Klaus, Oliver. "Twenty leagues under the sea." *MEED: Middle East Economic Digest* 47, no. 37 (September 12, 2003): 28.
[40] *Ibid.*
[41] *Ibid.*

surprised the world with the unimaginable. If there was ever hope for completion of a project of this magnitude, it could be found there.

II. HABITAT DESIGN

1 Habitat Programming

One of the principle tasks in designing a submersible structure is to determine its use. Currently, most underwater installations fall into two categories: Research or leisure. The research habitats are seeking to further the body of scientific knowledge concerning the oceans and related disciplines. Habitats tasked with leisure are providing a novelty to restaurant patrons and hotel guests. Each of these types requires a completely different structure to achieve its goals. For example, stations concerned with scientific research are designed to operate at ambient pressure. This means that the pressure inside the habitat is equivalent to the pressures in the surrounding water. This allows researchers to enter and exit the habitat without decompressing. However, lengthy decompression is required to return to the surface.

In Leisure habitats, the opposite is true. Visitors are more concerned with an easy transition between the surface and the habitat rather than moving into the water. This requires the structure to hold back the pressure of the surrounding water and allow the interior atmosphere to be equal to that on the surface. In the new paradigm of underwater construction, it is conceivable that habitats will need to have better continuity with the urban setting than the underwater realm. This drive will cause most, if not all non-scientific habitats to be designed for one atmosphere (surface pressure).

In conjunction with the unification goals of most comprehensive plans, underwater structures will undoubtedly seek to become an integral part of the city that they inhabit. Rather than becoming a disconnected structure far offshore, these habitat types may be included as a component of the city's urban design. To be included in this vision, underwater structures must increase their utility to the city. By diversifying their program, undersea dwellings may provide housing, commodities, power, or attractions for an urban waterfront. Because of this, new undersea building types may develop a more sustainable program by incorporating a mixed use or workforce housing components. An important principle of sustainability, workforce housing on the site of employment would be of great benefit to those living in the underwater setting.

It is conceivable that the new habitat type will not be one concerned with any single use. They will not resemble the small, single use stations of the past. They will most likely be a diverse complex of uses, responding to urban setting, and extending it to the sea. Comprised of residences, multi-family units, restaurants, classrooms, public spaces and possibly even power stations, it will embody many of the principles of urban planning. The new undersea habitat types will need to adhere to the existing urban setting and match the diversity of the built environment. By incorporating a cornucopia of uses, it may maintain its value as an appendage of the city.

2 An Undersea Landscape

Choosing a site for an underwater complex will rely as much on the urban context of the city as it does the composition of the sea floor. The sites should be chosen so that the habitat will seamlessly adhere to the existing waterfront condition and act as an extension. Additionally, it should respond to the changing conditions of the environment and prepare the city for prosperity with the rising sea.

2.1 Undersea structures and Urban Planning

It is often assumed that structures placed offshore are isolated and independent from their counterparts on land. However, imagine a community that actually incorporates undersea developments into their waterfront plan. Underwater installations could become an integral part of the community network by providing power, housing, entertainment, recreation, and even transportation. Because the sea is unencumbered with obstacles, undersea complexes provide a unique opportunity to incorporate transit systems that connect two portions of land that were otherwise geographically isolated. Whether using the undersea complex as a surface platform, or occurring below in an acrylic tunnel, rapid transit could be made possible by sea. This would reduce congestion on land and utilize a resident workforce in the undersea dwellings.

Planning an undersea structure will involve just as much discussion about urban context as it will about subsea conditions. Becoming a useful part of the city, as well as utilizing the existing infrastructure will be a critical task in the design process. Identifying opportunities for both the waterfront condition and the subsea structures will be difficult, but developing a symbiotic relationship with urban landscapes will ensure the viability of underwater installations in the future.

2.1.1 Ecology

One of the great dualities of siting this type of development is in regards to environmental concerns. On one hand, the placing of any undersea structure will disrupt the existing marine life. Structural pilings, pipelines, cables and other engineering elements impact the sea floor and its inhabitants. On the other hand, the presence of the structure may become a magnet for new and more diverse marine creatures. This means that undersea structures do not necessarily need to be placed in the center of a pristine coral reef. Vibrant ocean views may be achieved, even in barren areas, because of the structure's natural appeal to marine life. Over time, artificial structures have the potential to become even more populated than their neighboring habitats. For example, in Delaware, 600 subway cars were submerged as part of an artificial reef program. This new site is estimated to have increased the fish population in the area by a factor of 400 and increased angling trips by four fold annually. [42]

2.1-1 Artificial Reef Off Oahu

Artificial structures such as these have the ability to stimulate economic growth through improvement of the ecology of the waterfront area. With a new diverse presence of marine life, tourism may grow. Monterey Bay has seen resurgence like this on their Cannery Row. An area that was once a polluting industrial sardine packaging plant is now a thriving kelp forest. This is largely in thanks to the re-tasking of these buildings and the addition of the Monterey bay Aquarium.

---

[42] "ARTIFICIAL REEF FORMED BY SUBWAY CARS." *Civil Engineering (08857024)* 78, no. 7 (July 2008): 35-35. *Academic Search Premier*, EBSCO*host* (accessed December 3, 2008).

Other environmental improvements may be realized if the occupants sponsor a reef rehabilitation program (as seen at the Red Sea Star). Coral propagation, kelp planting and other environmental enhancements can help restore the surrounding area to a healthy state. This not only serves to help the immediate environment, but also increases the beauty that is observable from inside the habitat. By increasing the health of the surrounding waters, residents of underwater installations are improving their view.

2.2 Connections

A final consideration to site selection is to include cues in the natural environment that may allow occupants to connect with the conditions outside. On the surface, we may look out a window and know the atmospheric conditions. Trees waving, clouds rolling, rain falling, are all tools that we use to know what the weather is before going outside. Likewise, that connection to outdoors is important underwater. It would be desirable to have indicators in the undersea environment that can express the conditions of the sea. For example, kelp bending in a current, sand ripples from strong waves, or whitecaps spilling from blowing winds. These indicators will help residents feel connected with the conditions of the environment, even if they cannot swim to experience it firsthand.

Placing undersea structures is somewhat more difficult than placing a building on land. Though the site is rather open, it must be linked to both the urban and undersea conditions. In addition, environmental and weather conditions must be balanced to produce a safe, prolific structure. Once these conditions are mitigated, the underwater element of a waterfront plan will undoubtedly serve to improve the conditions both above and below the water.

3 STRUCTURE

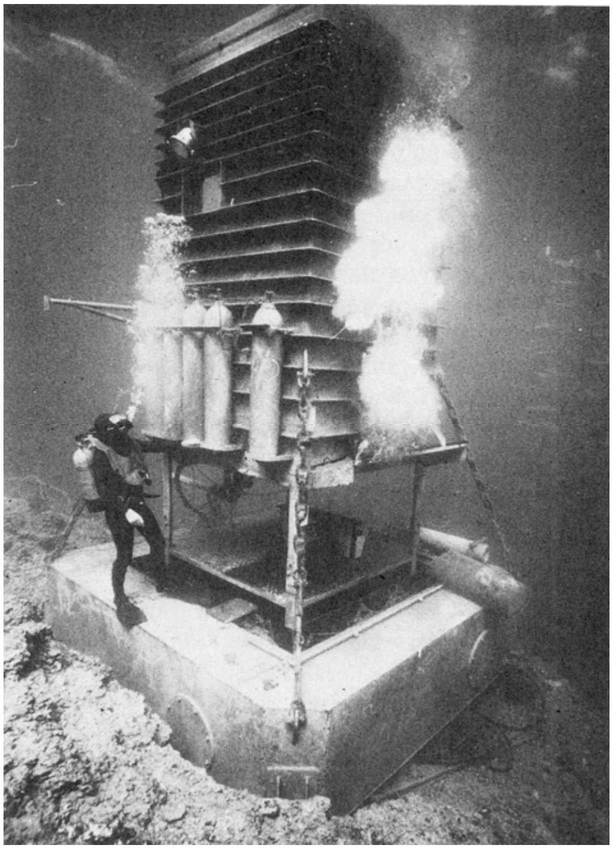
The major concern of undersea habitats will be withstanding the greater pressure of their surrounding environment. As a habitat's depth in seawater increases so does the ambient pressure. The general rule is that for every 33 feet submerged, the pressure will increase by one atmosphere (14.7 psi).[43] This means that habitats submerged in deeper water must take increasing measures to combat the pressure of depth. This is one of many reasons I propose that most habitats in the near future will be positioned at depths no greater than 60 ft. At this depth, the surrounding pressure should hover around 29 psi. Unlike deep diving submersibles, connections, seals and material thickness at this depth will not require such radical measures. For perspective, some skyscraper windows are rated to handle wind loading in the range of 100-30,000 psi.[44] Though intended for a different application, it is enlightening to see that materials capable of withstanding these pressures are currently used in the building trades.

Another factor considered in structural decisions is the movement of the marine environment. Waves and current can place additional pressures on submerged structures that should be accounted for. Aside from pressure, this movement of water may also shift sand and undermine the substrate that the structure is connected to. Careful consideration must be given to these conditions and the engineering elements that are used to support them.

[43] U.S. Department of the Navy. U.S. Navy Diving Manual. 1970, NAVSHIPS 0994-001-9010, 26
[44] www.kawneer.com

3.1.2 Foundations on the Sea Floor

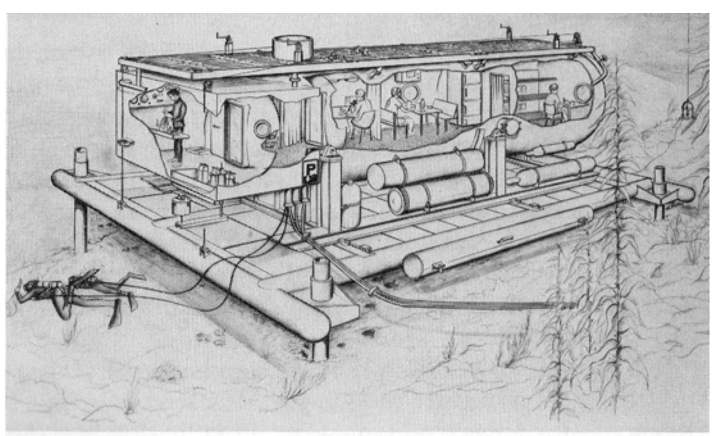
There are numerous techniques for placing a structure on the bottom of the sea. Historically, habitats have been ballasted with heavy weights of iron and sand to rest on the bottom. Ballast was needed because the habitat displaced a greater weight in seawater than its own weight. As explained in Archimede's principle, the structure needs to weigh more than the weight of the water it displaces in order to sink. Once heavy enough, some landed on feet that could be adjusted for leveling. Some habitats have used anchors to winch themselves to their depths. Though rudimentary, the methods of ballasting and anchoring were temporary and allowed them to be moved to other locations.



2.2-1 Anchored Habitat

Modern habitats have taken a more permanent approach. Some installations, like the Red Sea Star poured entire foundations on the sea floor for their structure to be adhered to. The large platform creates a very secure base. This eliminated the need for ballasting, given the weight of the footing structure. They were able to pour this massive slab because the area that they had chosen to develop was largely uninhabited by significant marine life. A massive structure such as this may not have been prudent in a more populated environment.

Most habitats have chosen the less invasive approach of driving pilings to which the structure is attached. While the process of driving the pilings into the substrate is not a delicate matter, once the pilings are installed, the habitat has little contact with the sea floor. It may rest only slightly above, leaving the remaining sea floor untouched. In addition, this configuration allows only the pilings to be a permanent addition to the bottom. The rest of the structure may be removed, recovered or serviced without compromising the bond between the pilings and the sea bed. The disadvantage of this system is that ballast must be included to allow the structure to sink. However, this ballast may be incorporated in thickened concrete elements or other internal structures.



2.2-2 Artist's Sketch of a Habitat on Pilings

I feel that pilings provide the most sensible solution for most offshore installations. They are the least disruptive and most flexible method of establishing a presence. The only areas impacted are those which occur at the exact site of the piling's insertion. The rest of the habitat may be suspended above the bottom to permit ocean currents and marine life to interact on all sides of the installation. In addition, the benefit of servicing the habitat while maintaining the piling's position is a huge economic advantage. The habitat may be removed and serviced much more economically and thoroughly at a dry dock site. The habitat may also be changed, augmented, renovated or replaced and still use the same foundation system. This brings a great deal of value to these locations. The site may be re-tasked to accommodate an infinite number of designs for a myriad of uses. Once installed, the supporting structure on the sea floor may far outlive the usefulness of the habitat that it was originally designed for.

By hovering just above the sea floor, one creates the condition where the view below is just as, if not more, important than the view above. Whereas views on the surface are connected to the horizontal landscape or to the sky, the limited visibility of the undersea world may develop a new take on this convention. The abundance of life that occurs in a small segment of reef below may far outweigh that of a large vista on land. With a structure that is suspended over the reef, one may find that the view to the nearby sea bed, even directly below their feet, offers far more interest than the views offered by the limited visibility in some marine habitats.

3.1.3 Sealing the Environment

The reality of underwater life is that in order to experience the sea, man must be separated from it. The largest object that stands between the resident and the sea is the habitat's bulkhead or hull. Simply put, the bulkheads are the floor, ceiling, and walls of the structure. They carve out the interior volume and define separations and uses.

Previous habitat hulls were constructed from pressure vessels, railroad tankers, and other repurposed containers because of their existing airtight seals. However, their unimaginative forms do little to carve out experiences inside.

Newer designs use a combination of materials to achieve volumes and separations relative to the functions of the spaces, not just the confines of a cylinder. Penetrations, openings, and services can all be planned to optimize performance, but must also avoid compromising the integrity of the hull. For example, an essential feature of every underwater habitat is a port to observe the surrounding environment. However, this critical feature has historically been the weak point for a habitat's structure. Ports vary in size from peep holes, a few inches in diameter, to entire rooms of acrylic. The connections of these panels to the more robust structure of the hull are critical details. Most connections are carried out by compressing rubber o-rings into channels carved into each surface with bolted flanges. The compression of this element keeps moisture out, so long as it is in good condition and the mating surfaces are free of imperfections. Other sealing techniques include rubber gaskets, threaded seals and welded connections.

Hull penetrations can occur for electrical services, telecommunications or diving hatches. The latter may be excessive in shallower installations. A lock-off chamber or compression chamber could be used to transfer divers to the sea. While this feature may be a viable option on some undersea stations, it embodies another failure point for the bulkhead. If habitats are placed in 60 feet or less, there is little need to discharge a diver at depth. It would be more prudent to allow maintenance divers to enter the water at the surface. A submerged diving chamber would be a complex addition with little benefit. Unless habitats exist at extreme depths at one atmosphere, there will be little need for it in future designs.

4 MATERIALS

Just like the structure, shape and program are unique to each design, so are many of the choices of materials. The most advantageous are those which are in widespread use in the building trade, are easily installed, easily serviced, resistant to corrosion, and remain watertight against changing pressures. The following is a discussion of the materials that fit those descriptions and their adaptations to underwater use.

4.1 Steel

Most undersea habitats to date have been constructed from steel. Some steels have great elastic properties and can withstand changes in pressure well. Additionally, it is a readily available material commonly used in construction. It can be welded together to form permanent, water tight bonds. And, these welds can be serviced underwater.

Although steel is a principal choice for most habitat structures, it has a major disadvantage when confronted with the corrosive nature of seawater. To prevent this, protective coatings are normally placed on both the exterior and interior of steel submersible structures. These coatings will ensure minimal contact with corrosive elements and increase the lifespan of the structure. In addition, most habitats install sacrificial anodes to combat galvanic corrosion. Galvanic corrosion takes places when an electrochemical reaction occurs between the seawater and the metal. Anodes offer this effect a more preferential material to attack, thus sparing the more critical parts. These anodes, normally made of zinc, are replaced often to reduce the corrosive effects. The maintenance of these anodes will need to be a consideration for the economy of future habitats. Decisions like these are essential in habitat design, in that, most habitats are not cheaply or easily serviced. This is especially true of critical hull structures. Though these anodes have been successfully used for many years, future habitats may use an electrical current to provide cathodic protection. By negating the seawater's corrosive electrochemical charge with an artificially induced electrical current, upcoming habitats may be able to provide their structures with an additional veil of protection.[45]

[45] James W. Miller and Ian G. Koblick, *Living and Working in the Sea,* 1984, 149

4.2 CONCRETE

Surprisingly, one of the more promising materials for underwater structures is one that has been present for a very long time. With its versatility and strength, concrete has the ability to provide a complex, strong and nearly impervious skin for potential installations. Authors Ian Koblick and James Miller relay their affinity for this material:

> "The use of concrete for submerged hulls probably will increase in the future because of the material's advantages of low cost and ease of fabrication (University of New Hampshire, 1972). Concrete has excellent strength qualities under hydrostatic pressure loads and excellent durability in seawater, and it may be used readily for the construction of complex shapes. With concrete, wall thickness of large habitats can be increased as necessary to achieve a neutrally buoyant structure, eliminating the need for additional ballast materials or massive anchoring systems. Permeability of seawater in concrete is not a problem, and hull strength is maintained both with and without various penetrations. The use of polymer-impregnated concrete results in an even more impermeable, stronger material." [46]

Years after the publication of their book, the reality of their statement, as well as the technology of concrete has matured. Ferrocement, carbon fiber reinforcement, and even coatings that allow concrete to heal itself, have been developed. These technologies will increase the safety and flexibility of underwater installations.

One major aspect of concrete's appeal is that it is a readily available material that is currently in widespread use. Many tradesmen are already trained in its

---

[46] James W. Miller and Ian G. Koblick, Living and Working in the Sea (New York: Van Nostrand Reinhold Company 1984), 144.

application. According to some, it is the "most used and most researched construction material today."[47] Numerous studies have been conducted on its resistance to strenuous conditions. Additionally, it is a versatile material. This is due to the fact that additives may be incorporated to give very basic ingredients some extraordinary properties. Additives like steel, lime, cellulose fibers, carbon fiber, and even air can change a mixture's properties to respond to each unique purpose.

There are numerous applications of concrete, many of which already exist in a submerged condition. Sea walls, levees, piers, jetties, pilings, and bridges have all stood the punishment of the ocean environment. Because the material has already proven its resilience against the sea, it becomes a viable option in choosing materials for planned undersea dwellings. In addition to its adaptability and strength, cement can be formed into nearly any conceivable shape. When combined with advanced reinforcement strategies, like ferrocement and fiber reinforced concrete (FRC), it becomes a versatile component of underwater construction.

4.2.4 FERROCEMENT

Ferrocement is not unlike standard reinforced concrete. It is similarly composed of a cement mix and steel reinforcement. However, it differs in the density of the steel reinforcement used. The American Concrete Institute defines it as:

> "Ferrocement is a type of thin wall reinforced concrete construction, where usually a hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh. Mesh may be made of metallic materials or other suitable materials."[48]

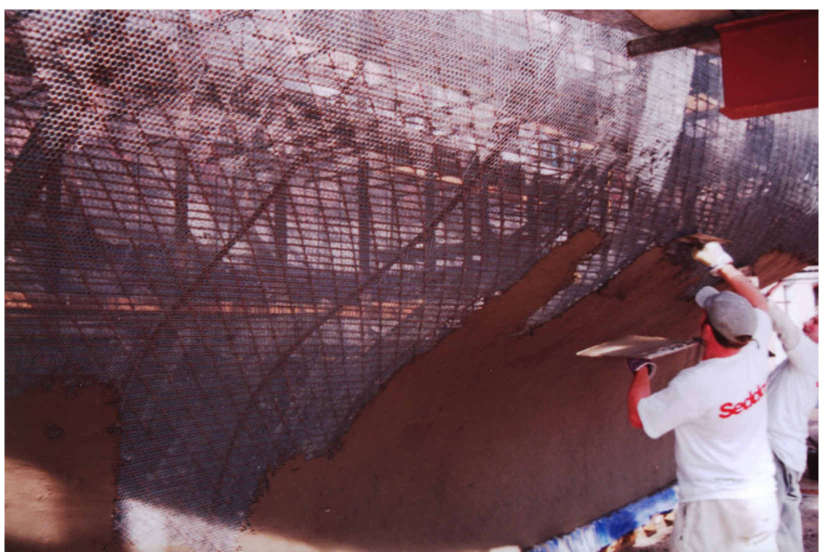
---

[47] Daniel, James I. and Surendra Shah, eds. Fiber Reinforced Concrete: Developments and Innovations. Detroit: American Concrete Institute, 1994, 91

[48] American Concrete Institute. "Ferrocement-Materials and Applications". Detroit: American Concrete Institute, 1979, 6

The mesh supplies additional reinforcement and creates a far greater mortar to reinforcement ratio. As implied by its name, there is far more steel in ferrocement than would be found in traditional reinforced concrete. This increase in reinforcement allows the structure to be much thinner and much more resilient against tension loads. Some even insist that ferrocement is merely "mortar impregnated reinforcement."[49] Regardless, the material can be made thin, strong and in a variety of shapes.

Because of the additional steel structure, it is found that hardly any formwork is required to make complicated shapes.[50] Therefore, the unique forms that may be required in underwater habitats can be constructed more efficiently. Another benefit is that limited skilled labor is required in most applications.[51] The simplicity and versatility of this material makes it a logical choice to alleviate some of the complexity of developing underwater.



4.2-1 Ferrocement Boat Under Construction

Currently, ferrocement is used in buildings, water tanks and boats. Its role in boating is perhaps its greatest testament to its imperviousness to seawater, flexibility,

[49] *Ibid., 11*
[50] *Ibid.*, 3
[51] *Ibid.*

and resistance towards pressure. There have been two manufacturers of ferrocement boats, as well as countless home-built versions. The Samson and Hartley companies have built numerous ferrocement boats, many of which are still in use today.

Although the technology of ferrocement has been widely used, the limit of the technology has not been reached. Studies are being conducted in incorporating this method of construction with other concrete technologies, like fiber reinforcing. By combining the two techniques, fiber reinforcement can help ferrocement overcome localized damage from impact loading.[52] The entrained fibers help to spread loads and increase flexural strength, while reducing the density of the mesh reinforcement that would otherwise be required.[53] This means that the concrete will maintain its flexibility while also increasing its resistance to cracking and puncture.

4.2.5 Fiber Reinforced Concrete

Another technology in concrete production is fiber reinforced concrete (FRC). This method of construction uses fibers of steel, carbon, cellulose, polypropylene, or other material to replace or augment the steel reinforcement that would normally be placed in a reinforced concrete structure. One of the distinct advantages to this technique is that the addition of short, randomly distributed fibers of reinforcement reduces the adverse effects of shrinkage and cracking.[54]

Shrinkage is a normal part of the concrete curing process. Additives may be included to reduce this, but the most common response is to install control joints at given intervals in the slab to isolate cracking to those areas. However, in undersea conditions, cracking is not a favorable condition, whether controlled or not. Therefore,

[52] *Ibid., 82*
[53] *Ibid.*
[54] Daniel, James I. and Surendra Shah, eds. Fiber Reinforced Concrete: Developments and Innovations. Detroit: American Concrete Institute, 1994, 1

the addition of fiber reinforcement will be a necessary component of the concrete composition.

The major concern is that cracks in the shell may induce unrecoverable leaking in an undersea habitat. Though the flexural strength of ferrocement will lessen that risk, the added benefit of fiber reinforcement's resistance to cracking and impact will augment the safety of the enclosure. The FRC provides local reinforcement throughout the mixture, meaning that each impacted site has reinforcement dedicated to that site. These fibers will help to spread the loads of impact throughout the surface of the panel and decrease the likelihood of cracks forming. In a test by the American Concrete institute, researchers found that steel reinforced concrete reduced the maximum crack width by 90%.[55] Moreover, the permeability of the material is decreased. In a test by the National Institute of Statistical Sciences, examiners found that "at higher levels of cracking, steel reinforcing fibers clearly reduce permeability" and that "more steel reduced permeability."[56]

Despite all its advantages, concrete with entrained steel fibers presents some problems undersea. The aggressive environment may attack the exposed fibers in the mixture, causing further damage like cracking and spalling. To overcome this, some steel reinforcement is available with an epoxy or resin coating. This protects the steel from the corrosive salt environment. However, changing the reinforcement to a non-corrosive material would be the most prudent route. Carbon fiber has proven to be a very proficient reinforcing material for concrete. The American Concrete Institute suggests that:

---

[55] Daniel, James I. and Surendra Shah, eds. Fiber Reinforced Concrete: Developments and Innovations. Detroit: American Concrete Institute, 1994, 1

[56] Rapoport, Julie, Corina-Maria Aldea, Surendra P. Shah, Bruce Ankenman, and Alan F. Karr. "Permeability of Cracked Steel Fiber-Reinforced Concrete," National Institute of Statistical Sciences Technical Report Number 115 (January 2001).http://www. niss.org/technicalreports/tr115.pdf (accessed December 1, 2008), 4

"The advantage of carbon fiber reinforcement over steel, polypropylene or glass fibers is in finishability, thermal resistance, weatherability, ability to mix high volume fractions and long term chemical stability in alkaline and other chemically aggressive environments. Further, the use of carbon fibers is not associated with any potential health hazards as does the use of asbestos fibers. These benefits along with the reported improvements in the mechanical properties make carbon fiber reinforcement a propitious proposition."[57]

They also include that carbon fiber is the most commonly used micro fiber and that costs have decreased with the development inexpensive pitch-based carbon fibers.[58] For undersea uses, carbon fiber's greatest feature is that it will not corrode in the harsh seawater environment. This will greatly improve the concrete's resilience in this difficult setting.

4.2.6 Applied Coatings

Despite the bouquet of concrete technologies one may compose, there is a certain degree of reality that cracks will eventually occur. The technology discussed to this point has served to reduce the size, frequency and permeability of those cracks. Once cracks are formed, engineers must seek additional repair and mitigation techniques. Though numerous patching techniques could be used, technologies exist where the concrete may heal itself, without human intervention.

One company has developed a coating called "Penetrol." This coating can be applied after the concrete is cured, or added to concrete mix. The chemical lies dormant until it senses the presence of water. Once Penetrol is exposed to moisture, it reacts to form a crystalline structure. This structure essentially seals the crack from

---

[57] Daniel, James I. and Surendra Shah, eds. Fiber Reinforced Concrete: Developments and Innovations. Detroit: American Concrete Institute, 1994, 92

[58] Daniel, James I. and Surendra Shah, eds. Fiber Reinforced Concrete: Developments and Innovations. Detroit: American Concrete Institute, 1994, 93

moisture penetration. If the coating senses a new rupture, it will reconstitute with the new moisture path and continue to occlude leakage.

Chemicals like these add another level of safety to the shell of an underwater habitat. The redundancy and comprehensiveness of these systems will create spaces that can not only survive their environments, but also respond to changes in their conditions. The application of these responsive and adaptive technologies is what will set undersea structures apart from their land locked counterparts.

4.3 Composites

In evaluating alternative materials for habitat construction, consideration should be given to newer composite structures like fiberglass, carbon fiber, glass reinforced plastics (GRP) and Kevlar. These materials may be combined with resins to produce a strong, impervious, and non-corrosive structure for future habitats. The SAM suit, a one atmosphere submersible, achieved depths of 381 meters with a structure of GRP.[59] These materials have been successfully assembled in firefighting SCBA cylinders. A Kevlar wrap is used as an exterior coating for an aluminum core to reduce its susceptibility to puncture, corrosion and heat. This assembly is lighter than conventional air cylinders and can operate at pressures over 3000 psi. In addition, the deep diving submersibles of Graham Hawkes use composite fiberglass resins forms to combat the pressures of the deep. These materials provide his vessels with a corrosion resistant structure and strong protection against his record breaking depths.

An additional benefit is that the composite materials may be easily molded into any shape. Materials like these will allow future habitat designers to respond to the

[59] Haux, Gerhard F.K., *Subsea Manned Engineering*., Carson: Best Publishing Company, 1982. 402

needs of the spaces contained. This will permit them to create spaces that are not limited to the layout of retired hyperbaric chambers. Much like the amorphous blobs of Kunsthaus Graz by Peter Cook, habitats may have the freedom to be amorphous and sensitive to their environment and their function.

4.4 Acrylic

A critical component of all undersea habitats is a method to view the outside world. According to author Jerry Stachiw, "to work effectively under water we must be able to observe effectively."[60] Viewports may vary from the pinhole openings of deep diving submersibles, to entirely transparent rooms. The decision of the size and shape of these windows is influenced by many factors. The first is material.

Acrylic plastic is the primary choice for submerged optical elements. "Unlike glass, plastic does not fail catastrophically, but with ample warning to the occupants of the undersea vehicle. It is, in virtually all respects, a gracious host."(Stachiw, 1982)[61] Acrylic is also chosen over other plastics for its superior optical quality and weather resistance.[62] It can be easily shaped when heated (thermoforming) and can be machined by using woodworking tools and basic machine shop equipment.[63] Additionally, its chemical composition may be adjusted to meet a variety of needs. Its versatility, security, and ease of use make it a logical choice for the undersea environment.

Currently, transparent acrylic panels are used in aquariums, submarines, undersea habitats and aircraft, just to name a few. Stachiw states that "Its use in today's undersea vehicles, habitats and diving systems is so catholic that one must

[60] Stachiw, Jerry D. *Acrylic Plastic Viewports.* New York: Marcel Dekker, 1982, iii
[61] *Ibid.*
[62] *Ibid., 55*
[63] *Ibid., 66*

occasionally wonder how we ever managed to do anything at all without it.[64] To date, the largest acrylic panel in existence belongs to the Aquarium at the Dubai mall. It measures 32.88 meters wide, 8.3 meters high and 750 mm thick. Panels like these are not restricted by the material, but by the limits of the manufacturing facilities. Therefore, future acrylic facilities may be capable of larger, more complex elements.

Despite the strength of large rectangular aquarium panels, the most effective pressure resistant window is a spherical shell.[65] Combinations of these efficient spheres and cylinders can be seen in the proposal for the Poseidon habitat in Fiji. These shapes are so large and unique, that owner Bruce Jones had to develop his own acrylic manufacturing facility.

Windows designed for use in underwater habitats must be created in accordance with the standards developed by the ANSI/ASME Safety Codes Committee on Pressure Vessels for Human Occupancy. As of 1984, windows designed on these bases have never been attributed to loss of life due to window failure.[66] These standards are widely accepted by not only submersible designers, but insurance societies, regulatory agencies, and classification societies.[67]

[64] *Ibid., iii*
[65] Stachiw, Jerry D. *Acrylic Plastic Viewports.* New York: Marcel Dekker, 1982, 251
[66] *Ibid.*, v
[67] *Ibid.*

5 SYSTEMS

The systems required for a single atmosphere, near shore structure, may not be adversely different from those found in a modern skyscraper. If near shore structures remain connected to a city's infrastructure, the systems involved become far less demanding. Offshore, independent structures face far greater challenges in waste, energy and sustenance. Therefore, civil connections may become a determining factor in undersea development. Despite this, there are a few systems that may require specific solutions.

5.1 LIFE SAFETY SYSTEMS

Although unlikely, the possibility exists that one may to need mitigate a disaster in one of these enclosures. Fire retardant systems, escape routes, and protected areas of egress will be important considerations when planning undersea structures for habitation. Regardless of the scenario, each mechanism of failure should be evaluated and mitigated during design.

One of the larger concerns for a single atmosphere enclosure is the possibility of flooding. Because the structure is operating at a lesser pressure to the aquatic environment outside, a catastrophic leak could occur at great velocities. Certain designers have taken different approaches towards ensuring the safety of their occupants. One elemental response is the compartmentalization of water tight areas throughout the structure. By segmenting smaller areas, separated by water tight enclosures, occupants may seal the offending section of the installation, thus preserving the remaining portions until repairs can be made. Since a majority of leaks will occur gradually, occupants should have plenty of time to exit the unit and seal the enclosure. In the Poseidon habitat, these water tight sections may be sealed and individually removed for servicing. In this habitat, designer Bruce Jones has also integrated areas of refuge. These are locations in each compartment that may be used to wait for help if a catastrophic flood occurs. Therefore, there is a contingency available, even if one may not be able to contain the flooding waters.

Another common exit strategy for marine science habitats are breathing stations. Breathing stations, like the ones on the Sealab and Tektite missions are bells of trapped air that are stationed at intervals along an aquatic escape route. If an aquanaut was forced to flee the habitat, he or she may swim the short distance between these stations and make a safe ascent to the surface. While this strategy does not require long periods of breath holding, it may not be suitable for structures where untrained individuals are housed.

Regardless of training, it may be prudent to locate auxiliary air supplies or SCBA units at critical points throughout the structure. These units would not be for water escapes, but would be intended to facilitate evacuation in fire scenarios. Because the complex would be sealed to the outside environment and rely only on HVAC systems for fresh air, smoke inhalation hazards are high. As in skyscrapers, fire dampers should be installed on all HVAC penetrations to automatically isolate the offending sections and stop the circulation of smoke.

Overall, there is an absolute need for rescue and recovery systems to exist on undersea habitats. A multi layered approach for every plausible scenario will be the demanded of designers for these installations. If for nothing more than peace of mind, numerous and diverse recovery methods should exists so that multiple options are available to meet the diverse challenges of undersea scenarios.

5.2 Atmospheric Comfort Undersea

One of the wonderful qualities of the undersea environment is that the temperature is very consistent. Large fluctuations in temperature do not occur as they do on the surface. Therefore, mitigations to atmospheric comfort may be handled with more precision, due to the absence of wild seasonal changes.

The heating and cooling loads for a single atmosphere installation will not be very different from a typical skyscraper. Tall buildings deliver pressurized air to occupied rooms and draw air from odorous places.[68] The pressure differential created in these spaces allows continuous flow of air and removal of offending sources of pollution. The environment outside is sealed to better facilitate this flow. This scenario is no different from the challenges faced in providing atmospheric comfort in surface pressure habitats. Very similar conditions exist, except that fresh air will be pumped down instead of up.

One feature of undersea HVAC that will differ from land based systems is that the system will need to be able to isolate sections if flooding occurs. With a system similar to fire dampers in large buildings these stations will initiate a watertight seal so that the remainder of the habitat may remain unaffected by flooding or removal of a section of the habitat.

Previous underwater habitat installations have been plagued with comfort issues due to the high humidity of their enclosures. Because all of these were open to the sea at ambient pressure, the constant presence of moisture created uncomfortable humidity at normal temperatures. Single atmosphere habitats will not need to contend with this issue. Despite the inconvenience of not being able to swim directly out of one's bedroom, these habitats are sealed from the outside waters and should experience very little rise in humidity.

5.3 Lighting Undersea

The goal of lighting installations undersea is to counteract the blue glow of the ambient light filtering through the water. If left to ambient conditions, underwater enclosures would be nearly devoid of red tones. This occurs because water filters the light spectrum. As depth increases, more of the spectrum is removed. Red tones are the first to disappear and blues and violets are the last. With no ambient red light,

[68] Stein, Benjamin and John S. Reynolds *Mechanical and Electrical Equipment for Buildings.*

interiors look blue and skin tones appear pale and discolored. One author even suggested that the introduction of mostly blue light would have a depressing effect on residents.[69] In addition, full spectrum lighting is important for human health. It has been found that adequate lighting is necessary to maintain circadian rhythm. Without it, serious health risks may follow.[70]

Overall, lighting should adhere to the same standards of the building trade, with the exception that warmer hues of lamps may be beneficial to counteract the environment's blue glow. The installations should also contain full spectrum lamps for daytime use, to maintain a healthy circadian rhythm.

---

[69] Magoroh Maruyama, Aesthetics and the Environment in Outer Space, Subterrainean and Underwater Communities (Futures: April, 1984), 161

[70] Pauley, Stephen M. "Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue," Medical Hypotheses Vol. 63, Issue 4 (2004), http://www.sciencedirect.com/science/journal/03069877 (accessed December 3, 2008)

6 Ancillary Technologies

As a coincidence to its presence in the sea, an undersea dwelling can act as a platform for other marine technologies. Production of electricity and hydrogen may be just two of the many commodities that underwater stations may be able to manufacture. Despite some installation's proximity to shore and urban infrastructure, incorporation of these technologies will augment the feasibility of independence from shore. By incorporating production technology into its design, these dwellings may supply their own energy needs or even the energy needs of their adjoining cities. Also, by incorporating production facilities into undersea complexes, jobs are created within the structure. This adds another layer of the sustainable component, in that employees may live and work on site.

6.1 Electricity

Though the sea has been heavily relied on as a food source, some individuals propose that we may soon be harvesting a great deal more from it. In the near future, the sea may provide another level of sustenance for mankind by delivering electricity through wind turbines, wave energy, ocean thermal energy conversion, hydrogen and even solar power. The ocean environment may be what provides us with the most modern necessities of life, further strengthening our affinity with the sea.

6.1.7 Wind

The open sea is an area for wind to blow unobstructed. Coastal cities have the advantage (and sometimes disadvantage) of being the first to meet that wind. To capitalize on this, undersea platforms could be used as a structure to which wind turbines are attached. Because they occur offshore, the undersea complex could be situated on the front line of harnessing unencumbered ocean breezes. They avoid the high cost of land in near coastal conditions and exist in an area where they are not a danger to people.

In addition, most coastal cities enjoy a diurnal flow. This means that as the land heats up during the day, it causes air to rise, drawing cool air from the sea. In the evening, the hot air cools and descends over the ocean to start the cycle again. This produces steady afternoon breezes in most coastal locations. This predictable occurrence could be harnessed as an energy source.

6.1.8 Wave Energy

One very visible energy source embodied in the sea is waves. There are few who have been in the water who would question the power of these rolling elements. Coastal cities and offshore structures have the ability to harness the energy of these natural events through several emerging technologies. Though most methods are still undergoing testing, the current models present some fantastic opportunities to create clean energy.

Wave energy is basically wind energy stored in the ocean environment. As wind blows across the sea, it progressively transfers its energy to the surface of the water. Essentially, wave energy is a way of harnessing winds from far offshore. According to the British wind energy association, wave energy could displace 1 to 2 billion tons of CO_2 per year from the burning of conventional fossil fuels.[71] Additionally, the 2004 EPRI report Offshore Wave Power in the US: Environmental Issues states that "given proper care in site planning and early dialogue with local stakeholders, offshore wave power promises to be one of the most environmentally benign electrical generation technologies." [72]

[71] Companhia Da Energia Oceanic, S.A. 2008. "World's First Commercial Wave Power Project Goes Live: Babcock & Brown, EDP, and Efacec Join Forces in the Development of Wave Energy." http://www.pelamiswave.com/news.php?id=26 (accessed December 4, 2008)

[72] Holzman, David C. 2007. "Blue Power: Turning Tides into Electricity." *Environmental Health Perspectives* 115, no. 12: A590-A593. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).

6.1-1 Pelamis Wave Energy Converter

Several companies are engineering devices to harness this inexhaustible energy source. One is Pelamis Wave Power. Pelamis has developed a snake-like system of buoys called the Pelamis Wave Energy Converter. It harnesses wave energy through the articulation of joints within its design. When the joints are manipulated, their movement is hindered by hydraulic rams which pump oil to rotate a turbine. The machines are designed to be placed in large arrays in 50-70 meters of water and approximately 5-10 kilometers offshore. At these locations, the system may better harness the large open ocean waves. Each unit is rated to produce up to 750 kilowatts. However, depending on the waves, they will produce an average of 25-40% of their designed output. This makes each machine capable of powering approximately 500 homes.[73] The company has officially opened its first wave farm off the coast of Portugal in September of 2008. The array of 3 energy converters is the first stage of a larger project that will contain up to 25 machines.

[73] Pelamis Wave Power. "The Pelamis Wave Energy Converter." http://www.pelamiswave.com/content.php?id=161 (accessed December 4, 2008)

Another emerging group is Ocean power Technologies. Their product is the PowerBuoy. As the buoy rises and falls, it drives a piston structure inside. This operates a turbine anchored to the ocean floor. They boast that a 1 megawatt array would price power at 7-10 cents/kilowatt and a 100 megawatt array would price at about 3-4 cents. This is including the cost of the equipment and maintenance costs.[74] The technology is currently in place off the coasts of New Jersey and Spain.[75]

An array of these systems could provide significant power for an offshore facility. Since the ocean is constantly in motion, this power source is abundant, though variable. Because of their proximity to this energy source, undersea installations could easily include this technology as part of their energy portfolio.

6.1.9 Ocean Thermal Energy Conversion

Ocean thermal energy conversion (OTEC) is a technology that harnesses the potential energy contained in a temperature differential existing between deep water and surface water, in tropical oceans. This idea is appealing to underwater structures because of its potential for cheap, clean energy. Currently, it is viewed as an inexhaustible resource. Harnessing this energy source is conducted through one of three different systems, the closed cycle, open cycle and hybrid system. Each system has its advantages and disadvantages.

6.1.10 Closed Cycle

A closed cycle system uses a working fluid in an evaporator to achieve an increase in pressure and creates vapor to run turbines. Ammonia is the preferred

---

[74] Gawel, Richard. 2005. "Offshore Power Generation Making Waves." *Electronic Design* 53, no. 6: 26-26. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).
[75] *Ibid*

working fluid for testing in the US, while Japan prefers Freon.[76] These chemicals have a low boiling point meaning that little warming is required to turn them from a liquid into a vapor. The warm sea water pumped from the ocean's surface warms the liquid ammonia which vaporizes and spins the turbine. Once through the turbine, the ammonia vapor is cooled by the cold seawater that has been pumped from thousands of feet below and the ammonia is returned to a liquid. Then the cycle is repeated.

6.1.11 Open Cycle

An open cycle system does not use an additional working fluid. Instead, it uses sea water as the medium to produce vapor. Warm sea water from the surface of the ocean is sprayed into a vacuum. The sea water evaporates to create low pressure steam which then spins the turbine. The steam then travels to the condenser which is cooled by the deep, cold water. One major advantage of an open cycle system is the production of fresh water through the evaporation and condensation of sea water. It is possible to produce up to 800,000 gallons of fresh water per day, per kilowatt of installed power capacity.[77] The fresh water from this system could meet the water needs of the entire submerged facility.

6.1.12 Hybrid Cycle

Hybrid systems combine components from both cycles. They use a working fluid other than sea water and produce potable water as a parallel system. Systems, like the Kalina Cycle© produced by OCEES International attach a fresh water production unit onto a closed cycle system. This unit produces potable water by processing the seawater through an open cycle system that has no turbine. This allows water to be produced more efficiently. The warmed seawater, in turn, heats the working fluid which spins the turbine.

---

[76] Yuen, Paul C. Ocean Thermal Energy Conversion: A Review, p. 4
[77] "Fresh Water Production From an Abundant Resource," 15 September 2002, OCEES International, <http://www.ocees.com/mainpages/Freshwater.html>

6.1.13 Locations for OTEC energy

OTEC facilities rely on a temperature difference that exists between surface water and deep water in the ocean. In order for this to be a viable system for an underwater complex, this difference in temperature must be near 40° F (22°C). This condition primarily exists in tropical waters between the 20°N and 20°S parallels, in water approximately 3,000 ft. deep. This places Hawaii in a prime location for OTEC testing. The deep water occurring near Kona, Hawaii has operated as the test bed for early experiments such as mini-OTEC. OTEC operations could possibly occur in areas such as the Gulf of Mexico, Florida, Puerto Rico, Japan, Singapore, Vietnam Samoa, Tonga, the Philippines, and thousands of other tropical locations.

6.1.14 Problems with OTEC

One of the primary problems with an OTEC plant is its lack of efficiency. Most OTEC plants using the rankine cycle are only 3-4% efficient. This means that in order to produce any significant amount of energy, the size of the plant must be enormous. Current technology may prohibit its use in undersea structures. Current proposals are heavily subsidized by the government, but still do not meet their financial needs. In 2002, Sea Solar Power proposed a 100 kilowatt floating system. It was estimated to cost 250 million dollars to construct.[78]

Long term environmental impacts of drawing cold seawater are still unknown. There are the obvious problems with intake screens affecting wildlife at depth. Also, cold seawater discharged near the surface will release trapped carbon dioxide (a greenhouse gas). This impact is thought to be minimal though, due to the fact that it is approximately 4-7% of the carbon dioxide discharge of a fossil fuel power plant.[79]

---

[78] "Sea Solar Power 100 MW hybrid cycle OTEC plantship design," 2 February 2002, Phil Kopiske: OTEC News, <http://www.otecnews.org/articles/ssp100mwotec.html>

[79] "Ocean Thermocline Technical FAQ," Practical Oceans Energy Management Systems Inc., October, 2004, <http://www.poemsinc.org/FAQOTEC.html#3>

Discharging cool water near the surface may also affect nutrient levels and local sea temperatures. Increased salinity from fresh water production may also contribute to ecological problems. It is possible that these issues may create an imbalance in the ecosystem surrounding the undersea installation.

While a viable OTEC facility may be very far in the future, it is an exciting technology that could be incorporated into an undersea complex's energy portfolio. Once plants are efficient and reduced in size, habitats located in tropical settings may be able to utilize this colossal power source.

6.2 HYDROGEN

One of the promising energy opportunities that surround an undersea habitat is hydrogen. It burns clean, is an abundant resource on the planet, and makes up two thirds of water's molecular structure. Because hydrogen can be produced from water through electrolysis, underwater stations could potentially harvest some of that energy. Using an electrified cathode, electrolysis separates the hydrogen and oxygen molecules in water. The advantage is that the hydrogen is produced at a very pure level and there is no pollution at the process site. However, the disadvantage is that the use of electricity in this procedure causes greenhouse gas emissions from the power plants that supply it. However, if undersea structures were able to employ renewable sources for electricity (like solar, wind, OTEC, etc.) the process would be carbon neutral.

Another challenge with hydrogen production is storage. Hydrogen may be stored in pressurized tanks, in liquid form, in glass micro-spheres or even in nano tubes. Each storage method currently has problems. Storing hydrogen in pressurized tanks takes up a great deal of room and requires the use of compressors. Liquefaction requires only slightly less room but also needs chillers and highly insulated tanks. Micro technology is expensive and energy consuming.[80] For undersea use, it would seem that the pressurized tanks pose the more efficient solution. The undersea environment is vast and cool. The tanks could be quite large and stored at a constant, low temperature under the sea.

A viable application of hydrogen production for undersea complexes would be in energy storage. Because hydrogen is not as efficient as other fuels, its major potential is in the stockpiling of energy. This may be necessary because clean energy sources such as wind, solar, and wave energy may not always be productive enough to meet the energy needs of the site. These would include times when the wind is not blowing, the sea is calm, or at night. Conversely, there are times when this energy source is prolific and producing a surplus that cannot be used at that time. It may be possible for undersea sites to use this surplus energy to produce hydrogen. This is possible because scientists have recently developed methods of extracting hydrogen directly from seawater (instead of demineralized water), through electrolysis.[81] The surplus energy from renewable sources could be tasked with operating electrolysis facilities that would extract and store hydrogen. This hydrogen could then be used in a fuel cell to provide electricity when power generation falls below demand. The hydrogen could be stored in large tanks on the sea floor. Since space is not a concern on the sea bed, large pressurized containers could be utilized to stockpile the gas until it is needed.

Simply by being surrounded by water, undersea structures could assist urban areas in their endeavors for energy independence. By combining renewable energy

[80] Chen, Ping, and Min Zhu. 2008. "Recent progress in hydrogen storage." Materials Today 11, no. 12: 36-43. Academic Search Premier, EBSCOhost (accessed December 4, 2008).

[81] Zenta Kato, Koichi Izumiya, Naokazu Kumagai, and Koji Hashimoto. 2009. "Energy-saving seawater electrolysis for hydrogen production." *Journal of Solid State electrochemistry* 13, no. 2: 219-224. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).

sources with hydrogen energy storage, undersea installations may lead the way to a world free of fossil fuels.

7 FATHOMING DELIGHT

Intrigue and splendor in Architecture is impossibly difficult to quantify. What is it about a space that makes it beautiful? Is it the quality of light? The way you move through it? The colors, the forms, or some contemplation of every feature as it impacts your senses? In his document, "The Ten books on Architecture," the roman architect Vitruvius developed a simple mantra for the qualification of an architectural space: Firmitas, Ulilitas Venustas. This elegant phrase closely translates to firmness, commodity, and delight. It simply means that for a space to be considered good architecture, it must have a sound structure, be useful in its disposition, and be delightful to those who occupy it. While the first two are fairly straightforward, the final quality is harder to ascertain. In this section, I hope to delve into Vitruvius' third goal of architecture and describe the delightful aspects of buildings undersea.

The presence of water in any setting can stir a multitude of emotions. Depending on the quality of the body of water, it can convey power, tranquility, wonder, and reverence. In the book "Aquatecture" author Anthony Wylson introduces this by saying:

> "Water not only provides a basis for man's existence and a continuous challenge to secure its use, but it is a source of metaphysical symbolism, aesthetic pleasure and therapeutic value. Water gives expression to nature's moods and provides substance to seasonal change. Landscape is fashioned by water, which as cascades, resurgent sea or reflective calm, bears witness to a beneficial universe. "[82]

By introducing this element onto one's living spaces, it can become an integral part of daily life. Imagine waking to the soothing blue glow of an undersea sunrise, or walking down a hallway flanked by the cadence of undulating fish, sipping coffee while the waves roar far above your head, or listening to music with ripples of light dancing on the floor. Day to day experiences could be enriched by life undersea.

There is a great deal of calm associated with water environments. It can be used to relieve a multitude of stresses in architectural space. Charles Moore cites that "designers also use the qualities of reflection, depth, or the seemingly infinite surface of large bodies of water to relieve claustrophobia and expand personal space."[83] This idea is reinforced through a multitude of accounts by aquanauts in early scientific experiments. Their cramped surroundings were expanded by a porthole connection to the outside world. [84]

---

[82] Wylson, Anthony. Aquatecture: Architecture and Water. New York: Van Nostrand Reinhold. 1986. p. 3
[83] Moore, Charles. Water and Architecture. New York: Harry N. Abrams. 1994, p.200
[84] James W. Miller and Ian G. Koblick, Living and Working in the Sea (New York: Van Nostrand Reinhold Company 1984), 155

Another space that embodies this calm is the Huvafen Fushi Spa in the Maldives. The soft blue glow and the languid movements of sea life instill a sense of tranquility to visitors. The surroundings augment the relaxation of the treatments as visitors see and feel the presence of movement all around them. In today's world, people clamor for these calming experiences. The home has become a sanctuary from all of life's stress and turmoil. If the opportunity was present to incorporate the calming effects of submergence, like those found in the Maldives, homeowners may find their sanctuary even more profound. The quiet and the solitude that can be afforded to an undersea structure are unlike any experience found on land.

Another association to the serenity of submerged life is the correlation to baptism. Many religions like Christianity and Hinduism practice an immersion in water to cleanse and purify the soul. Whether consciously or unconsciously, each immersion offers an opportunity to feel renewed and disconnected from events passed. Tadao Ando recognized this phenomenon when he designed the Water Temple at Awaji Island, Japan.[85] Visitors

6.2-1 WATER TEMPLE BY TADAO ANDO IN AWAJI ISLAND, JAPAN

[85] Ando, Tadao. "Tadao Ando: Light and Water" New York: The Montacelli Press. 2003 pp. 118-123

enter the temple by walking down a path that takes them through the center of a large pool. As their eyes pass below the surface, they receive a similar peace to baptism before they even enter the space. Adding to the sanctuary qualities of a modern home, each time a person enters a submerged space, they are offered a comparable baptism. To achieve this in the home, the irreplaceable event is the moment of submergence. Moore recounts that "the most important thing to consider when making designs involving emotional contact with the water is the edge."[86] Residents must be allowed to experience the moment that their eye meets with the plane of the surface so that they can see the instant that they no longer occupy a terrestrial environment. The experience could induce a sense of release of the day's events and a renewal of serenity for their life at home.

A disconnection from life on the surface is a wonderful phenomenon of submergence. Many scuba divers report that only underwater can they truly live in that moment and release all of their worries on land. After all, at sixty feet deep, there is little they could do about anything anyway. There is a remarkable sense of apathy that occurs when undersea. The occurrences on the surface seem to have little to do with you. The wind, waves, and rain can all pass overhead without affecting you in the least. This disconnection combined with the idea of baptism and renewal would bring an entirely new level of peace and rejuvenation into the home.

Despite a subconscious separation from life on the surface, it is important for these structures to maintain a strong connection to the environment. The ability to peer outside of the space and ascertain information about the state of the world outside is crucial. Moreover, water is excellent at conveying some of these conditions. Near the surface, many atmospheric conditions can be observed. Wind, for instance is seen as whitecaps spilling over the tops of dancing waves and rain makes the surface shudder

[86] Moore, Charles. Water and Architecture. New York: Harry N. Abrams. 1994, p.204

with each droplet. Additionally, ocean currents and tidal changes can be added to the observable events. All of this permits residents to remain connected to the environment and evaluate its mood.

However, one major hindrance to the connection of man and the sea is the necessity to introduce a barrier between them. Even with modern SCUBA equipment, enclosures are required for man to survive in this foreign environment. This, of course, is a contradiction to the need to connect with one's environment. In the undersea development, one must make compromises and foster innovations to allow this connection to take place. This can be done in numerous ways. Naturally, this can be accomplished by varying the degrees of transparency in the structure. Penetrations of acrylic permit views outside, including above and below. In some cases, entire enclosures of acrylic can be used to give a person a feeling of complete submergence. In addition, the introduction of water into the spaces through the use of water features would further blur the boundaries of inside and out. Unfortunately, moon pools and other penetrations are not permissible in single atmosphere installations (they would flood to equalize ambient pressure). Instead, water must be introduced in controllable terms. Small pools installed on the interior can give the feeling of connection with the surrounding water. Since the optical qualities of water and acrylic are similar, a water feature with an acrylic bottom would appear unobstructed to the outside. It would appear as though the structure had a moon pool to access the outside environment, but the level would be safely controlled inside the structure. Also, waterfalls and other water features place on wall seams could appear as though the walls were cracked or open to the outside. Though these features may create uneasiness in some, others may appreciate the playful interaction with the element surrounding the structure.

Ultimately, these underwater spaces are about peace, serenity and harmony with the environment. However, to be harmonious with a changing climate we too must be willing to change. Installations like these allow us to better subsist with the changing conditions on the planet. Global warming and the associated sea level rise will undoubtedly modify our way of life. Rather than deny its occurrence, try to fight it, or adapt failing systems, undersea structures allow mankind to further understand and accept the changes taking place. Our ability to turn rising waters into a beautiful event is possibly the most delightful thing about the potential of undersea life. It allows us to embrace our relationship with the environment and the changes to come. As the sea rises, inch by inch, more of these adaptable structures become submerged, enriching the delight of the spaces inside. This turns fear into fascination and creates something delightful out of an event that threatened despair. Charles Moore states that "if we can effectively incorporate water's symbolism, history and physical nature, then our water and architecture can have a potential for wonder unmatched by any other material that we can include in our environments." [87]

[87] Moore, Charles. Water and Architecture. New York: Harry N. Abrams. 1994, p.199

III Alternative Future

1 The "Futures Image"[88]

In this section, I will be employing a "futures image" to help discuss the design proposal. This platform permits exploration of certain existing conditions and how they may develop into plausible scenarios. The scenario developed for this project facilitates the discussion and possible evolution of the undersea architectural paradigm. This exercise is necessary because today's market may not foster the demand for housing undersea, but plausible outcomes of current conditions exist where these installations may become more prolific and significant to the field of architecture

[88] Dator, Jim. "Images of the Future." Accessed November 17, 2008

It is important to mention that this is only one alternative view of what the future may become. And, although rooted in the current knowledge base, does not represent a future that is inevitable.[89] It embodies one perspective where individual ideas have culminated in a "preferred future"[90]. However, one should keep in mind that "The future cannot be predicted, but alternative futures can and should be forecast." (Dator)[91] This forecast should serve to facilitate thought and discussion regarding the architectural ideas proposed.

The future that I will describe is one in which man has been empowered to adapt. Innovation and determination has mitigated environmental changes that threaten our world. From this, a new facet of the urban landscape has developed.

1.1 THE YEAR 2060:

Over 50 years have passed since the climate change debates of the early millennium. In that time, many of the fears voiced by early apocalyptic scientists have been realized. Exceeding predictions by the Intergovernmental Panel on Climate Change (IPCC) in 2007, sea level has risen nearly a meter.[92] The unrelenting temperatures created by environmental degradation have caused the seas to advance, impacting coastlines worldwide.

It is largely accepted that the present conditions were the result of numerous environmental assaults by man. Deforestation, burning of fossil fuels, and the relentless intrusion of chemicals into the atmosphere had set in motion a great shift in the patterns of climate on earth. From as early as 2020, temperature increases were sufficient to cause many of the world's glaciers to completely recede. These changes in

---

[89] *Ibid.*
[90] *Ibid.*
[91] *Ibid.*
[92] United States Environmental Protection Agency, "Future Sea Level Changes." http://epa.gov/climate change/science/futureslc.html.

temperature also brought about wild and unpredictable storms. In the following years, coastal cities were battered by hurricanes and flooded by storm surges. These recurring phenomenons caused some to move their families to inland locations. However, many remained.

Most coastal land was becoming devalued. Some could not afford to sell their land for fear of homelessness. Long time residents sought to protect their investments by fortifying their homes in any way that they could. Some were able to lift their homes to be mounted on pilings. Others built sandbag and concrete perimeters around their yard. However, this did little when standing water seeped beneath their fortified walls. Because of this, sump pumps were used around many homes to lower the water level saturated into the nearby earth. Most recognized that these were temporary solutions, because the expectation was that conditions would improve.

The onslaught of weather caused many other problems. Ravaged by storms, oil companies could no longer sustain operations in coastal and offshore areas. Already afflicted with the scarcity of oil reserves, their installations were dismantled by hurricanes and high seas. By 2032, the remaining oil companies could no longer produce enough barrels to meet the world's demands. The Peak oil crisis had begun. Due to the sudden high cost of oil, automakers scrambled to employ the numerous alternative fuels that had been developed, but never used. In the interim, oil was a luxury that few could afford.

The scarcity of oil caused many transportation systems to fail. Because cars were no longer an option, public transportation was overwhelmed with demand. For several months, busses and trains were packed beyond capacity. Many businesspeople were forced to work from home. Those who could not telecommute moved very near to their places of business. Business districts were quickly engulfed with a need for housing. Prices in these areas skyrocketed as many businesses were forced to relocate to more residential areas or supply housing for their displaced employees.

By 2038, when alternative fuels and vehicles became widely available, many urban residents had already relinquished their need for automobiles. Their proximity to work combined with a revitalized public transportation removed their reliance on independent modes of transport. This radical change in behavior caused many city planners, like those in Los Angeles, to completely rethink their infrastructure. Freeways were demolished as suburban neighborhoods were rejected by the majority. Urban centers bustled with not only businesspeople, but families and children as well. Because of this, the newest city buildings needed to meet the demands of business, and the needs of the residential population that it would contain. In short, what was previously labeled as a mixed use building is now simply a standard of design.

As years passed, the sea continued to rise. In the forties and early fifties, the ice of Greenland disappeared almost simultaneously with the collapse of the West Antarctic ice sheet.[93] These events caused many to abandon their hopes of preserving their beachfront homes. Some cities sought refuge by erecting massive levee projects. Led by the Dutch, the 2040's saw countless levee projects undertaken. Low lying areas were seeking to be sheltered by a similar system of dikes that have protected the Polderlands for generations. Sons and daughters of the famed Deltawerken[94] project provided the engineering necessary to preserve some coastline.

As one of the top contributors to the global warming issue, and among the last to change, the United States was looking to regain credibility by accelerating the frontier of coastal fortification. Some of the most ambitious projects in the world have been undertaken by the US. With a government workforce not seen since the WPA, the

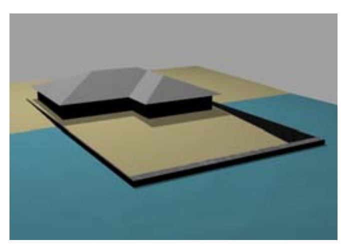
---

[93] David G. Vaughan, "How Does the Antarctic Ice Sheet Affect Sea Level Rise?," *SCIENCE 308* (June 2005): 1877-1878.

[94] http://www.deltawerken.com/en/10.html%3Fsetlanguage=en

2050's saw an ambitious system of fortifications proposed to protect the most crucial municipalities. Barriers were being erected around the country, targeting tributary areas like the Mississippi Delta and San Francisco Bay. By protecting these areas, the towns adjoining the connected waterways were also protected. However, many coastal sites would remain exposed. With their buildings facing imminent demise and their property mostly underwater, landowners sold their parcels for pennies on the dollar.

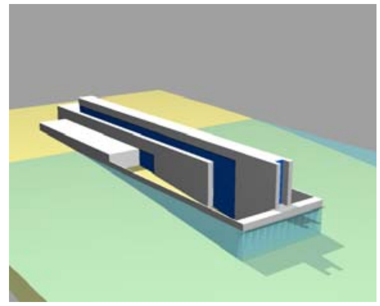
Philanthropic developers eagerly collected the depreciated land and sought to use it as an opportunity to create a new commodity in the housing market. Their situation was very unique. Up to this point, most land that occurred offshore of the mean high tide mark was considered public. However, because the land was owned before the water covered it, litigation determined that it could still be privately held, despite its submerged status. Because of this, developers could create installations in, on and even under the water. This opened and entirely new market for design. Not only were these homes perched on a location that was inconceivable to develop before, but they were constructed in such a way that they were able to accommodate the ocean as it rises. The vision was to create a style of building that was beautiful, useful and economic in its ability to adapt to changing climates.



1.1-1 Coastline Home with Improved Levee

Early designers began their endeavors by simply improving existing levee walls around homes. This inexpensive augmentation allowed the homes to survive much longer against rising water. However, due to the height of the walls, windows were cut and filled with thick Plexiglas, to allow a view outside. While these homes were occupied, residents could watch the water rise. Their acrylic windows even offered them a peek under the intruding waters. This became one of the nice things about flooding days. Families would gather around the windows to barbeque and watch the fish swim by.

Later, designers began to recognize the advantage of incorporating these windows in their buildings. Although the homes were occasionally inundated with water, the experience was actually pleasing. The soothing nature of an entire ocean's aquarium outside one's door was a commodity that some were pleased to have. Although this location required changes in lifestyle, it permitted those who had bonded with coastal locations to remain affixed to the sites they love.



1.1-2 Home with Levee Incorporated

To capitalize on this new feature, builders began to incorporate the sea walls into the walls of the home. The acrylic windows became larger and more prevalent in the interior spaces of the residence. Eventually, sections of some sites were excavated to allow full-time submerged viewing in the home. The splendor of submergence had been realized.

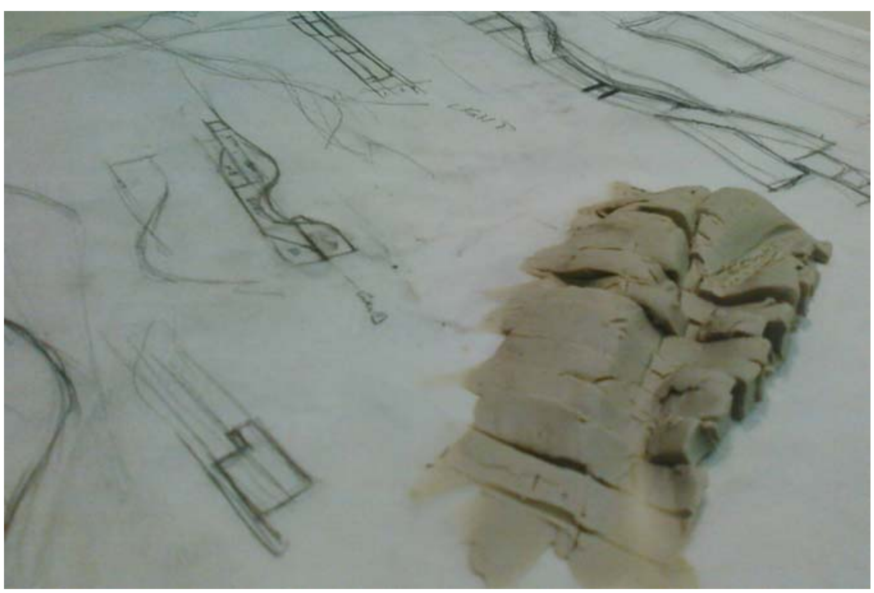
1.1-3 New Model of Coastal Home

This new model of architectural design breathed new life into some dilapidated coastal towns. Submerged residences were now the wave of the future. Not only did these residences allow a spectacular undersea experience, they were able to accommodate the imminent changes in sea level. With each passing year, the sea rises a little more and makes the experience even richer. Rather than becoming extinct with the change in climate, these homes become more prosperous as it occurs. This concept changed something apocalyptic into something beautiful.

Overall, this era of architectural design represented the new mindset of the people. Rather than fight nature, they choose to adapt with it. They wish to be more responsive to its changes. And now they live, knowing that even though the world is changing, their homes may adapt and respond. They will be able to subsist and live, enjoying the splendor of the rising sea.

2 THE DESIGN PROCESS

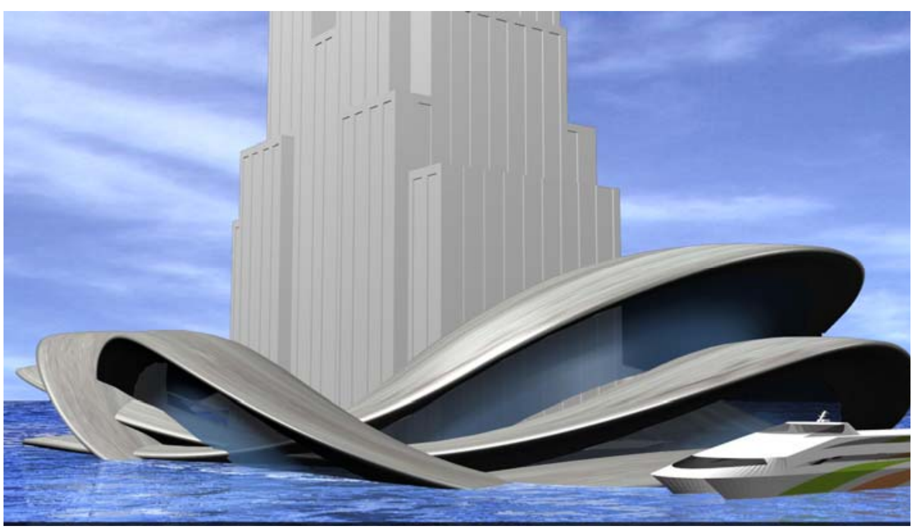
During the design process, many iterations of a design are created and discarded. However, from each evolution, lessons are learned that can be applied to the following concept. This design exercise was no exception. Therefore, to become better familiar with the final design, this section will examine the aborted designs and show how each one provided the final building with its attributes.



2.1 Existing Buildings

When first examining the problem of creating buildings adaptable to rising sea levels, one of the more logical interventions is to seek to retrofit existing buildings. Because there are trillions of dollars invested into coastal structures, it would be prudent to find a way to allow those buildings to survive in the changing environment. If these buildings were adapted, a buffer could be created that permits opportunities for interactions with the water while simultaneously maintaining a barrier between the structure and the sea. Newly created undersea plazas could provide unique experiences to building visitors, in a way that was not possible in their land-based context.

To execute a renovation of this magnitude, it was thought that the building would have to be substantial; not just in size, but in significance. As a preliminary investigation, I chose the empire state building a model. It was thought that this building would be historically significant, would contain space enough to be economical and occupies an area susceptible to flooding in the future. Additionally, it is an iconic building that may support an argument for preservation.



Although this scenario is logical, it presents some herculean challenges. One is that if we are to assume that the surrounding context of the building was sacrificial, we could also assume that the infrastructure would be sacrificed. Therefore, the building would need to become independent of all public systems. This includes electricity, water, and especially waste. Though not impossible, the costs associated with this conversion would be insurmountable. It would no longer be plausible for a building of even great importance to be preserved in this method.

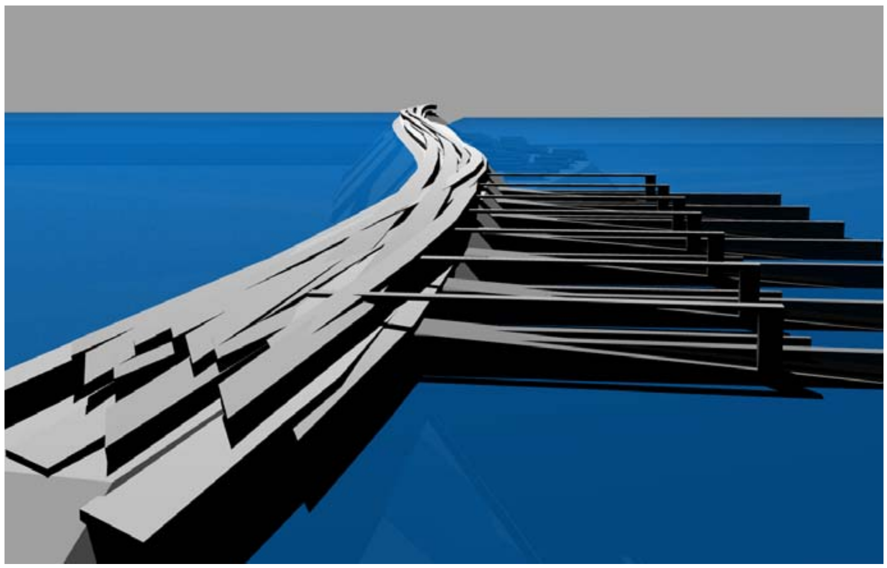
In addition to engineering issues, the architectural implication of preserving a single structure to forsake all others is staggering. Though Iconic to begin with, preserving only historically significant buildings in this manner does not seem prudent. It removes the building from its original context, which is arguably as much a part of the architecture as the brick and mortar. The image of a building sitting alone, atop a submerged city of ruins is more apocalyptic than visionary. Additionally, upon further investigation, it was found that the sea levels are not projected to rise the 30-40 feet that would create the planned underwater experiences around the building. Also, if the sea level was permitted enough time to creep to that level, the building would age into obsolescence and be likely beyond repair.

Ultimately, the greatest value in this early design was in developing the partí, or organizing idea, for the formal quality of the building. In seeking a partí to organize the spaces that protect man from the sea, one inescapably draws parallels to the maritime traditions. Generations of seafaring cultures have crafted a multitude of solutions to life on the water. Inspiration in this area is prolific because numerous innovations were necessary to allow man to survive both on and under the sea. However, despite the ever increasing technological prowess of mariners, it is impressive that one of the more critical practices has remained largely unchanged. The more artful traditions of marine knot tying has transcended generations. With nothing more than a length of rope, skilled mariners can resolve a multitude of problems. With repeated sennits and decorative turns, they turn practicality onto art. This thought sparked the idea of protecting buildings by wrapping them. Similar to a chafing guard on a a sailor's tool handle, the building could be wrapped in built spaces. As these spaces weave in and around one another, they create rooms, voids, walls, and openings. The swirling nature of the form lends itself easily to the natural forms of the sea, almost mimicking the waves around it.

2.2 The Levee

It was suggested that the economy preserving a single edifice was uncertain and that it would be much more likely that levees would be erected to preserve large communities. Therefore, for the next iteration of this solution, I researched the dikes of the Polderlands in the Netherlands. These areas currently exist below sea level and are protected by a series of dikes, levees and storm barriers. The engineers of the Deltawerken dike system are doing today, what many may need to do in the future; reclaim land from the sea. This idea seeded the thought that levees could be the new underwater space. Instead of piling rock or erecting steel fences, levees could be erected that had internal voids. These spaces would take full advantage of the bulk inherent to levee structures by containing uses pertinent to the urban context while simultaneously capturing the splendor of living undersea.

Because of the size of the levee structure, many programs outside of residential use were explored for nesting inside the form. Hydrogen production, OTEC, and seawater cooling were only a few of the systems that were proposed for the space. Even an undersea rail system was examined for connecting the two banks of the waterway that it straddled. The idea that this structure could supplant itself from a product of engineering to an extremity of the urban condition was very exciting.



The major dispute with the levee project was that it was fighting sea level rise rather embracing it. The overall goal is to create buildings that are about adaptation, acceptance and delight of the approaching water. The levees seemed to be a temporary solution and a denial of the impending changes. This contradiction would remove it from the list of usable concepts.

However, the innovation in this exercise was the addition of “clip-on” living units. In one section of the levee, residential units attached to the structure in rows. The units were self contained and modular, meaning that they could be removed for repair or replacement. This modular system was consistent with the ideas of other maritime city metabolists like Kiyonori Kikutake. The idea was that the units could be easily removed, which increased their serviceability and extended the useful life of the structure. The scale and repetition of these units would also influence later designs.

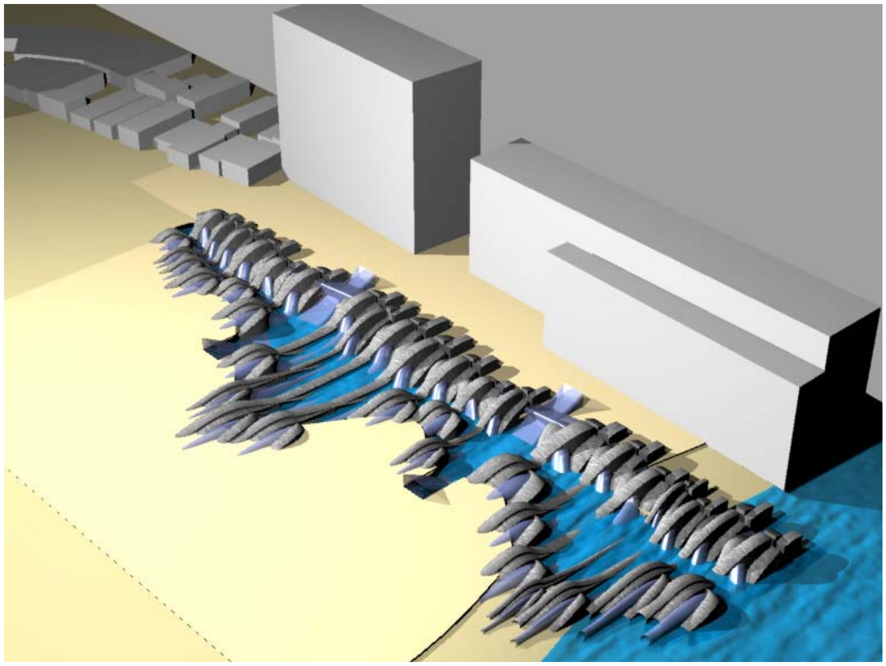
2.3 The Lagoon

Inspiration for this most recent iteration was derived from Peter Eisenmann. In a submission for the IFCCA Prize competition for the design of cities, he showed a huge complex repeatedly segmented along its short axis. Though colossal in scale, it fragmented near the edges to respond to the formal quality of the city on both sides. However, as the form approaches the center, it dissolves into something completely organic. This segmented form ignited the idea of containing the water inside the project, under controlled conditions, and responding to the city scale on the facades.

2.3-1The design of Cities Competition Entry by Eisenmann

One of the challenges inherent to the construction of an undersea building is that it is completely disconnected from land. Conversely, if one were to build it on land and wait for the water to rise, it would be awkward in the city landscape and could not realize its full potential for undersea splendor for many years. With Eisenmann's project as inspiration, the problem was solved by inviting water into the project under controllable terms. In other words, build a lagoon. Similar to the construction of a harbor, this waterway would allow water to permeate the boundaries of the beach and mingle in the urban environment. This condition would allow the building to straddle the water, thus creating a condition where it may respond to the city scale on both sides, but also dip beneath the water and enjoy the beauty of a submerged room.

Although these structures would be designed to ultimately become completely submerged, residents would not need to wait for decades of sea level rise to enjoy submerged life.



The deficiency of this scenario was that the formal quality was not conducive to underwater life. It did not contain the opportunities for the unique undersea experiences discussed in the document. Although It embodied the principles of the recent design by incorporating modular components, it neglected the lessons learned from existing building exercise. Therefore, the final design takes the original partí into account. It uses the knot-like forms to weave interesting spaces and create an environment conducive to undersea life. The hope is that it has absorbed the best lessons from previous studies and will be the best platform to discuss adaptation to undersea life.

3 The Design

"What I find is that when things have come out well they tend to assume a form which often surprises me when I finally stand back from the work and which makes me think: you could never have imagined when you started out that this would be the outcome. [95]

-Peter Zumthor

The body of research in this volume has led to the creation of this final design. Its goal is to represent the breadth of knowledge on the subject and facilitate further discussion on the topic of undersea life.

[95] Zumthor, Peter. *Atmospheres*. Basel: Birkhauser, 2006. P.71

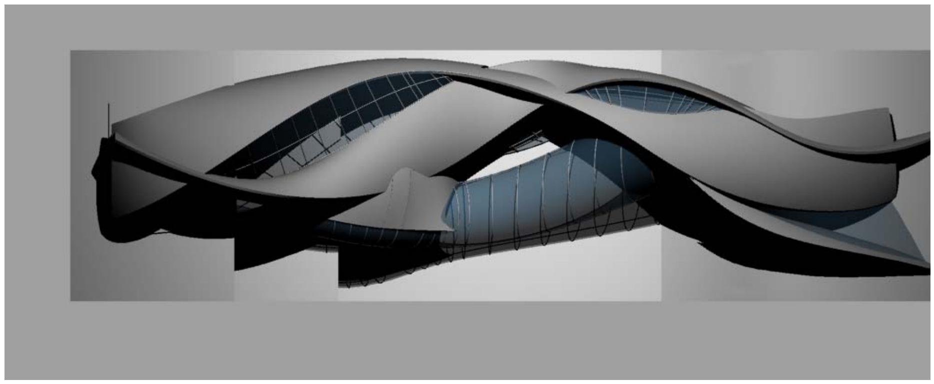
3.1 The Form

In evolving the final iteration of this design, many forms were examined. The goal was to locate a design that would relate to the environment on both a physical and metaphysical level. The structure should also permit the flexibility in creating vivid undersea experiences throughout the unit. In examining parallels in the undersea environment, forms that were conducive to the changing, flowing nature of the undersea world were explored. One of the most favorable images was that of underwater plants or kelp. The flowing, changing forms of the kelp fronds twist from horizontal to vertical and capture spaces. Their compiled knots create safe harbor for a multitude of undersea creatures. Their ability to define space, support life, and twist and change with the surrounding environment make it a logical analogy for an undersea building.

3.1-1 Kelp

Following the precedence of the kelp form, extrusions were created that transformed from wall to ceiling as it passed through the unit. This swirling form emulated the undulation of a kelp frond in the currents. Several of these forms were created and were woven into one another, thus creating the enclosure. Intersections that were not completely sealed were enclosed with acrylic windows. These windows were laced to create very unique experiences interacting with the surrounding water. From the outside, the form appears to compliment the rolling waves of the sea. The organic nature of the pieces almost appears to be born of the ocean, just like the kelp.

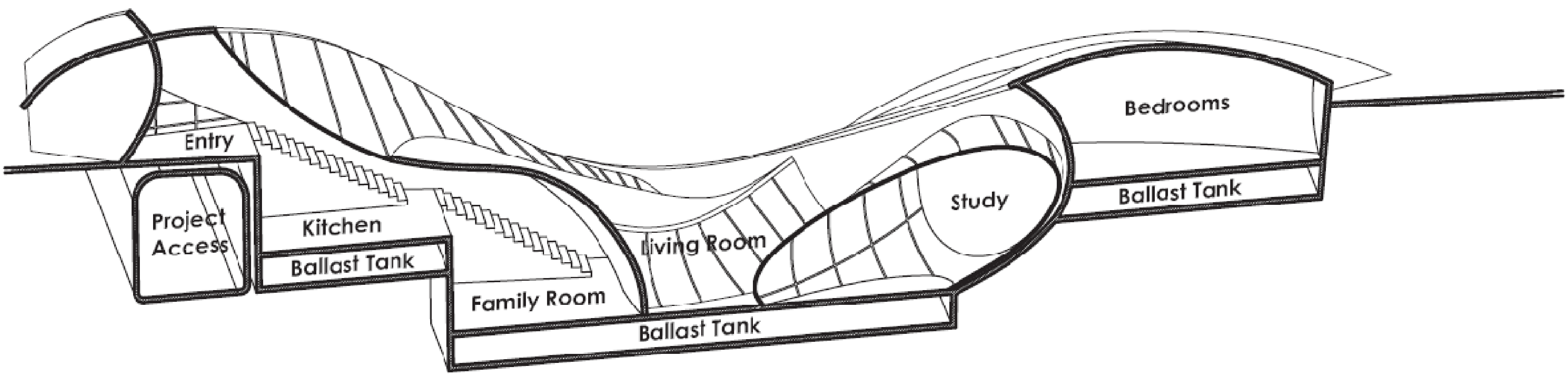
Overall, the unit is not a foreign object underwater. It complements its surroundings and embodies the ideal of adaptation, which was the genesis for the project.

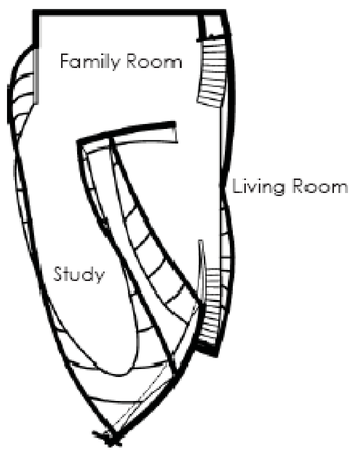


As kelp fronds dance about one another, they capture space. However, they also grant access to light. Openings can be crafted just as freely as enclosures with this system. The openings can push and pull from one another capturing either ocean or air between them. Due to the amorphous nature of the structure, it is flexible. This is because the knot form allows abstraction without complete contradiction of the original idea. This is analogous to the ideas that just because two leaves of seaweed are not identical; it does not mean that they do not complement each other, or that they were not born of the same roots. In the example, a courtyard of ocean has been detained by two rooms. The beauty of the system is that this undersea courtyard could be expanded, contracted or removed completely. This method of enclosure is not tied to a single arrangement. It can be adapted and evolved to each unique task without reinventing the partí. In addition, the composition of parts allows the project to create additional units, without affecting the overall design intent. Because of this, the structure may expand and repeat. Though each repetition may not be a duplicate of the one that preceded it, the variety of form allows the complex to remain versatile in its utility to the whole. Each piece will embody the swirling nature of the partí, but the partí allows it to adapt to the use that is required. Because of this, the composition may accept new pieces, in true metabolist form. Each piece may have a unique program that will maximize its value to the project. This flexibility will ensure its viability throughout its expansion. Unlike the rigid controls set upon units in projects like the capsule tower of Kisho Kurokawa, this project will accept new components, unique to the ones that preceded it, but born of the same ideals.

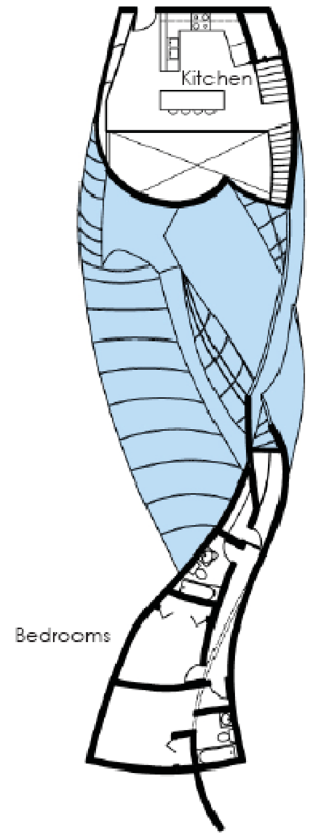
3.1-2 KISHO KUROKAWA'S CAPSULE TOWER

However, despite the utility of the design, structure is of concern. As discussed earlier, ferrocement is a promising material to meet this challenge. It has already proven its worth in crafting the complex curves of ship hulls, as well as, meeting the impervious needs large of water tanks. Because of its increased reinforcement, it is likely that it would be able to conduct the complex task of supporting these large, lofted shapes. Additionally, with the continuing advancement of concrete technology, it is reasonable to believe that lighter and stronger concretes will become available to make the structure even more feasible.

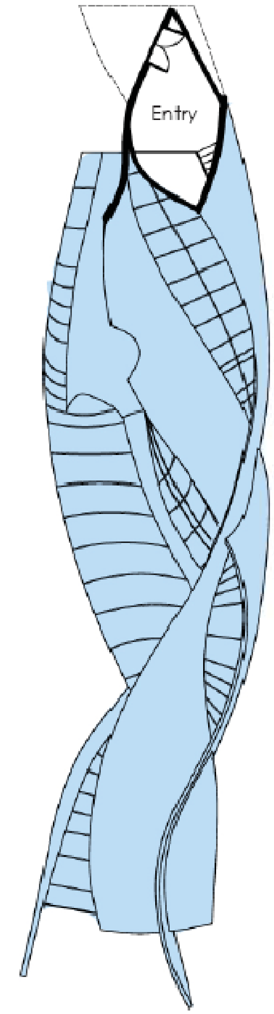

Entry
Project
Access
Kitchen
Ballast Tank
Family Room
Living Room
Ballast Tank
Study
Bedrooms
Ballast Tank



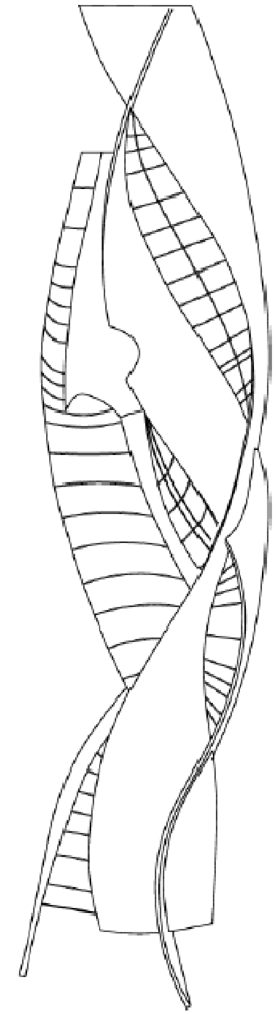
Lowest Level



Mid-Level



Upper Level



Roof Plan

3.2 Interior Spaces

The Interior spaces of this building receive the utmost attention. Because it is reasonable that residents could be confined to these spaces, even the experience of walking through the door must be carefully crafted. One must be able to experience both worlds in which the structure occupies. In this project, two entrances have been clearly separated. One is intended for the use of residents and the other for visitors. The entrance for visitors has been created at grade level, while the entrance for residents is near the surface level of the water. It is important that visitors to the project be made to walk the entire journey from the surface to the underwater spaces. They enter far above the waterline and progress downstairs. As they do so, their eyes gaze straight ahead to the large window before them. While they descend, the plane of the surface intersects their eye, until they are submerged. This is a critical experience for visitors. This is the event that separates this home from a visit to the aquarium. Instead of being supplanted to an underwater world, one is willfully and knowingly submerging themselves. In a similar experience to the Water Temple by Tadao Ando, the instant that they leave the world of the surface is blatantly understood. As they encounter the first landing they are met with the idea that they no longer occupy the surface of the earth. Additionally, as architect and author Charles Moore suggested the expansive view and connection to the outside environment will expand the perception of livable space. [96]

The residential entrance is located off of a shared walkway connecting the entire project. This walkway is located undersea and will ultimately be the only access to the units when the project becomes completely submerged. Views are limited from this path, but the unit doors open into a large open space in the home. This large space is valuable in dispelling some predisposed notions that undersea habitats are cramped

[96] Moore, Charles. Water and Architecture. New York: Harry N. Abrams. 1994, p.204

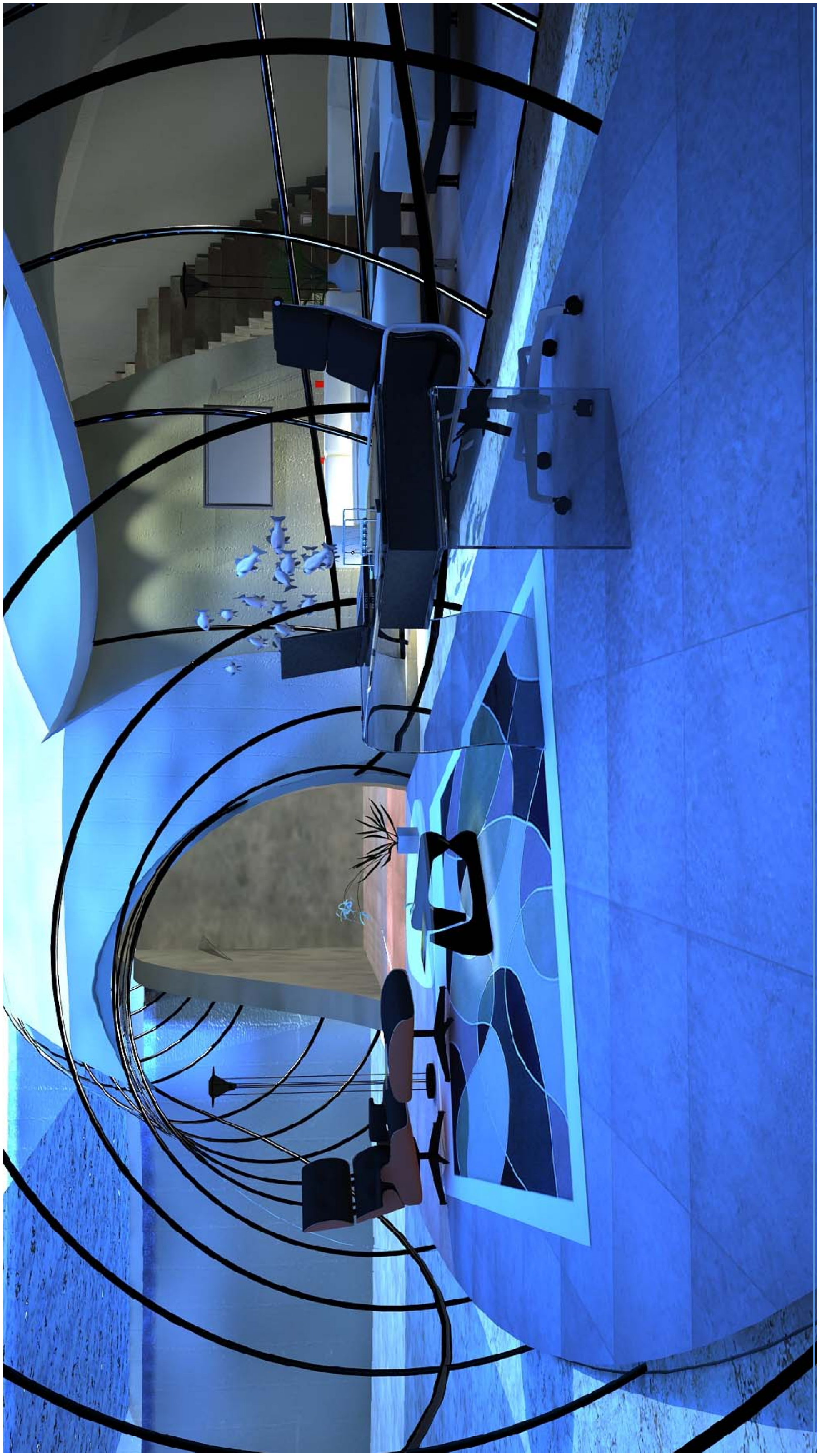
spaces. Upon entering, residents enter their kitchen/dining area and have an expansive view of the family room, study, living room and a view outside. A synopsis of the entire home can be viewed from here.

Because food is often the center of activity in a home, and one often wishes to drop off groceries when returning, the kitchen area is the first to be visited. Another advantage to this being the first room in the home is that it is one of the highest elevated. This allows fumes from the kitchen to be exhausted without passing through other rooms.

After leaving the kitchen, another flight of stairs down will take you to the bottom floor. The room you encounter here is the dining and family room. This space has some undersea views, but reserves much of the grandeur of the undersea environment for the more intimate spaces further inside the residence. It is more appropriately labeled as a space of transition. While it does have some undersea views, it remains bathed in natural light. It is located at the gateway for the most intimate and most completely submerged rooms in the project.

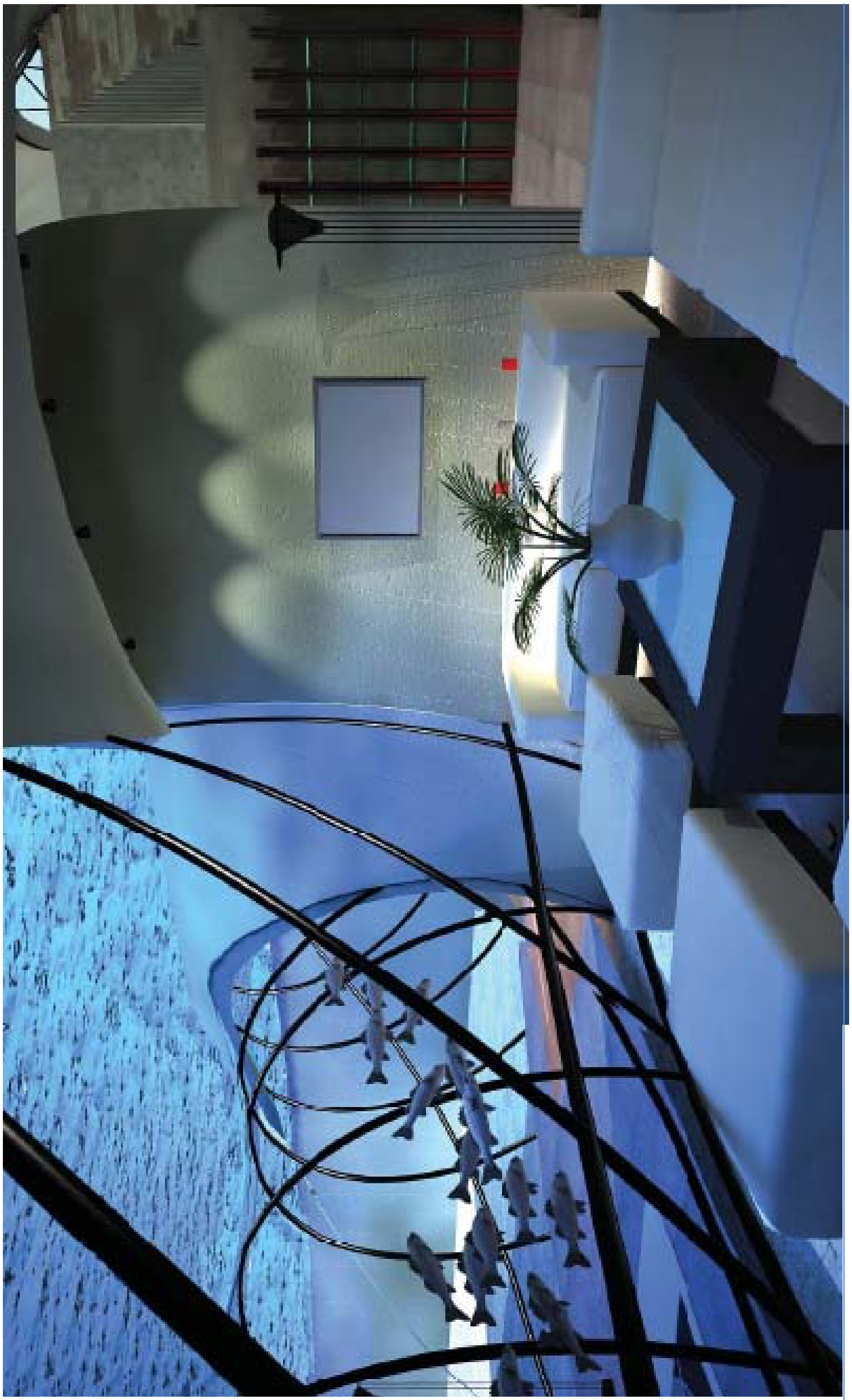
After leaving the family room, there are two rooms one may enter. One room is the study. The study is a unique experience to the rest of the home. It is an area of complete immersion. Once one has passed the threshold to this space, one enters the sea. The room is entirely acrylic. Similar to the moving walkway tubes of many marine parks, this space offers the feeling of being completely surrounded by water. I see this space as one of reflection. I view it as a place to accept the serenity of the surroundings and ponder in deep thought. The room could just as easily been a dining room or bath, but I think of this immersion as a focusing space, one of quiet and reverence. This is the room where one may fully grasp the feeling of living underwater.

View from Kitchen Towards Dining Room



View from Study

View of Undersea Courtyard from Eames Chair



Living Room

A different exit from the family room would take one to the living room. This is a room for visiting and conversation with guests. It is positioned adjacent to a large panel of acrylic which looks out onto the resident's undersea courtyard. While the study is a space of absolute immersion, the living room has more of a focused attention. The single wall opens the room to the sea, while the other walls offer warmth and privacy. I feel that this room offers a compromise between the warm lighting of surface based homes and the cool undersea glow of submerged spaces. It maintains the comfort and privacy of an average living room while maintaining an association with the calming effects of the undersea environment.

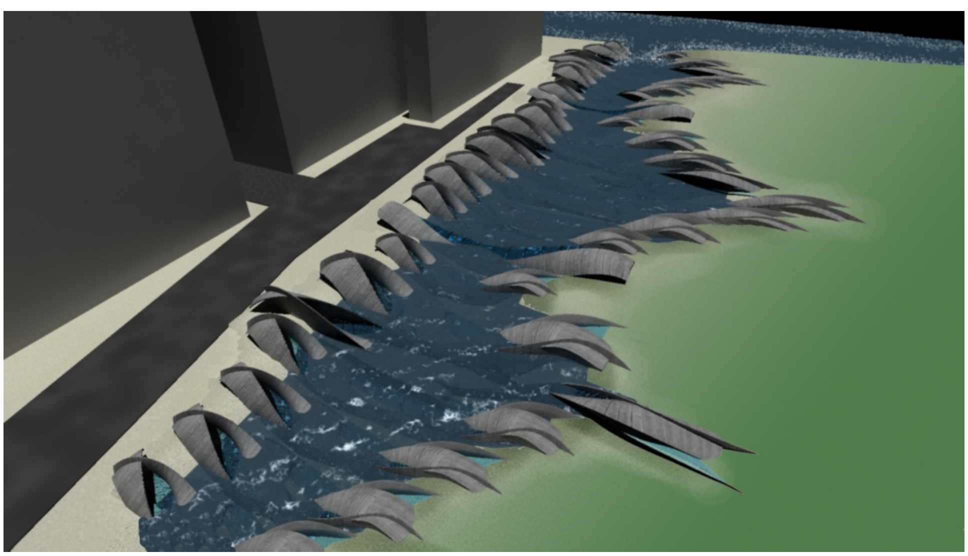
Between the living room and study is a small courtyard. Though miniscule, it captures a piece of the ocean for the resident's use. They could potentially plant a coral garden or sculpt a Zen masterpiece into the sand. It is their exclusive sea. I feel that this feature is crucially important. The home needs to interact with the sea. In this instance, the sea is woven in between two spaces. This interaction introduces the ocean environment into the living spaces. It starts to blur the idea that the sea is outside and I am inside. Although a boundary still exists, the water is now inside of the project as an undeniable piece, central to the focus of the undersea rooms.

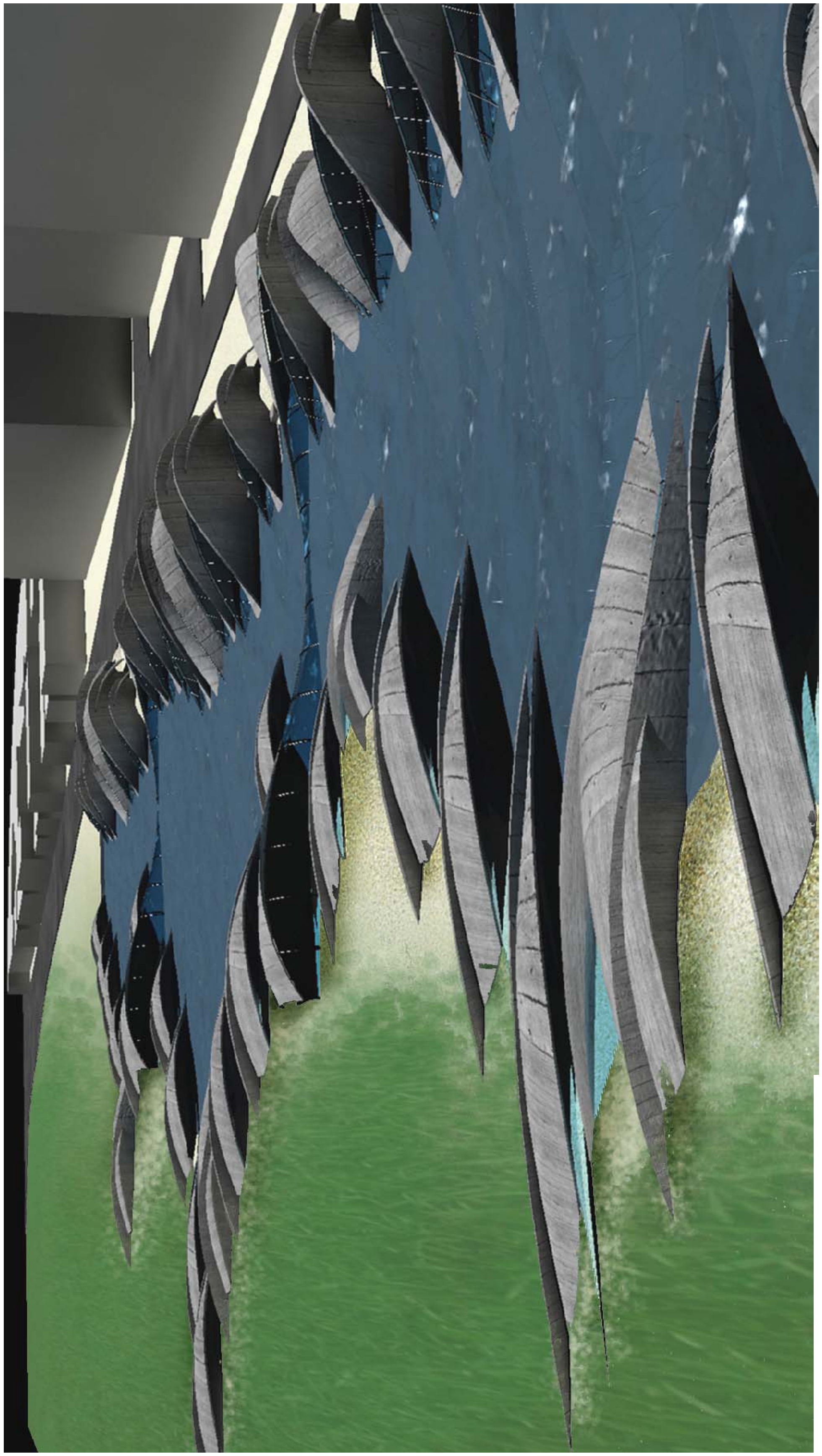
The living room is also the gateway to the bedrooms. Accessed by a small, intimate stairway at the rear of the living room, these are the most private spaces in the home. They have only a few openings to the outside. However, they are among the highest rooms in the project so as to facilitate egress. By being the highest rooms, they are safest in the event of flooding. Their airtight ceilings would trap air and prevent the rising of water. This would give occupants ample time to call for assistance and wait for rescue. Both sides of the home offer this type of refuge so that it would become nearly impossible to become trapped in a single room with no escape.

As a whole, the interior spaces are working to evoke all the emotions of living undersea while maintaining comfort and beauty. Every experience from sunlit rooms to total immersion is available.

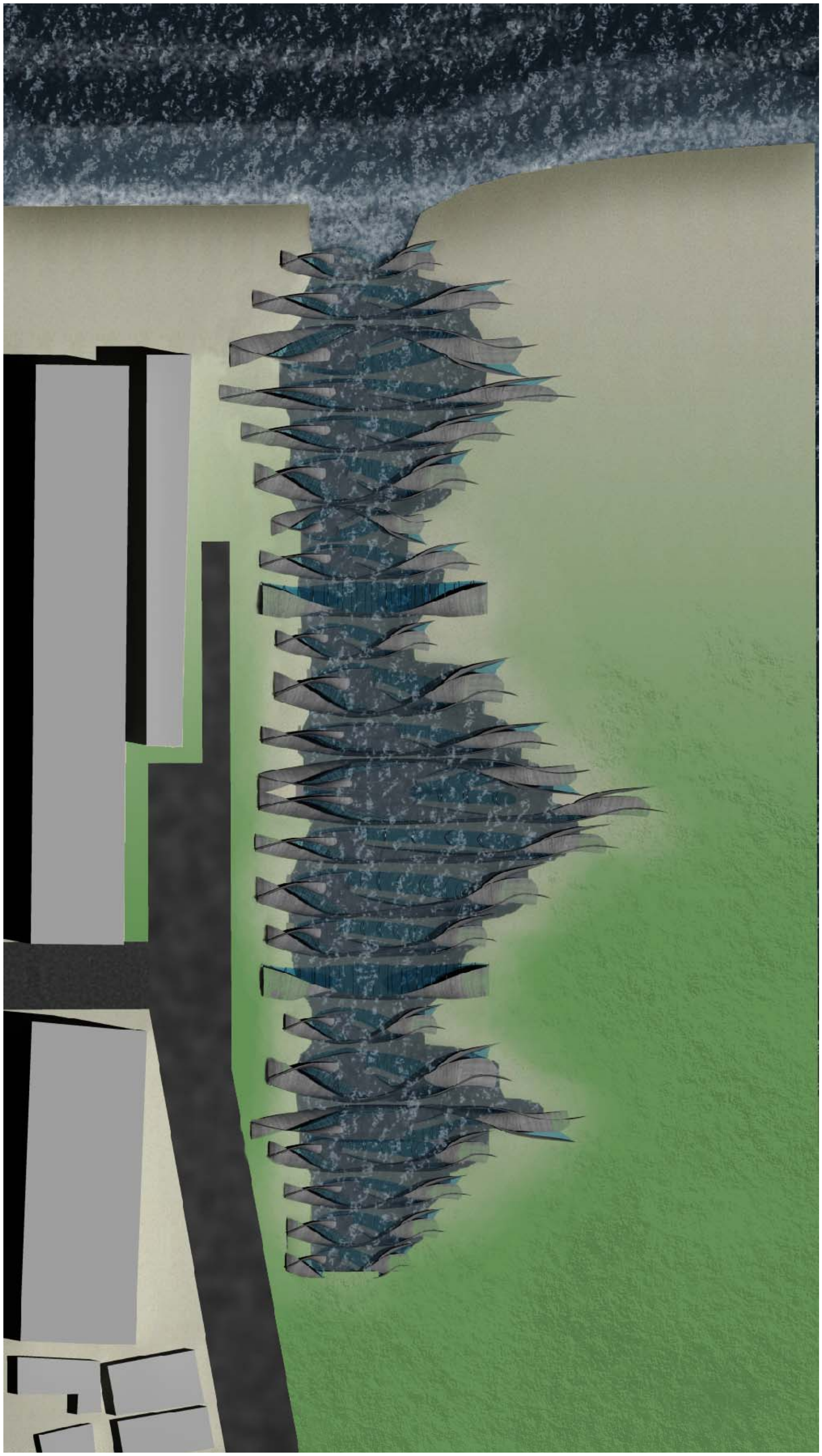
3.3 The Complex

One of the goals of the project's organization is that it may be added to as the needs of the project expand. The principles of growth and expandability are rooted in the ideals of early metabolic architects like Kisho Kurokawa Kiyonori Kikutake. Their treatises are rooted in the precedence of colonial animals like corals and other adaptable sea creatures. The animals cluster and grow in an amorphic way, to better adapt to their environment and serve the changing needs of the group. Likewise, in order to maintain utility to its occupants and adaptability as an undersea structure, the complex must be afforded the opportunity to grow and change. By multiplying the units across the site, subtle manipulations in form and program can ensure the diversity of uses for this project. As the needs of the project change, so can the functions of its parts. The program is not dictated from the outset. Instead, the program can be derived from the progressive analysis of the changing needs of the project, over the course of its life.





Complex View from South



Plan View of Complex

In addition, when the forms are repeated and gathered as a complex, they find interdependency. They each create eddies in the wave and current forces that protect the project next to it. Also, large common spaces can be developed for use in the density of the project. The expandability of this complex ensures that the project may continue to grow and adapt as demand increases for this style of living.

The siting of this project can be analyzed in many ways. If the main goal was integration into urban cores, the buildings could be constructed on land and wait for the rising tide. Of course, it may take a lifetime to achieve the beauty intended for the undersea spaces. Conversely, they could be constructed offshore. This would be ideal for the undersea quality of the spaces, but do little to incorporate the project into the current urban landscape. The ideal compromise in this situation is to allow the water to infiltrate the urban space; to accept the ocean into the project under controllable terms. In other words, create a harbor. In this scenario, the water is allowed to penetrate deeper into the urban center than the current beach would allow. This permits the units to occupy a space that is both involved with the urban cores, but also occupying a space that is undersea. By straddling a waterway, the project is able to take full advantage of undersea spaces and urban proximity. Progressively, these units will become submerged as sea level rises.

In order to maintain the longevity of the project, it will be necessary to service the units. Because of their location in shallow water and proximity to dry land, it is reasonable to assume that most repairs could be done on-site. However, if sea level were to rise dramatically and completely submerge the project, the on-site serviceability becomes complicated and decreasingly possible. Therefore, it may be necessary to remove units from their place in the structure for service. This can be done by allowing the unit to release from ballast or pilings and float to the surface. Because of the large volume of displacement in the units, it is likely that they will displace a greater volume of water than their equivalent weight. Archimedes' principle states that this will cause the unit to float. Once buoyant, the unit may be towed to a shipyard or other specialized facility for service and repairs. It is likely that the transportation and repairs at a specialized facility would be much more economical than the fees associated with offshore dive teams for on-site repairs.

The attachment of the units to the overall structure will be a complicated engineering task. The first goal is to attach the unit to the sea bed. This can be accomplished with anchors, ballast, or pilings. As stated previously, pilings are a favorable system and would likely be used. Short pilings with features that allow the unit to clamp into place would allow units the freedom for removal and replacement. However, getting the unit to the seabed is another challenge entirely.

The units would contain a certain amount of built-in ballast at the base of the structure. This would ensure that center of gravity stays beneath the water line and that the spaces will stay upright if the unit is floated. This is a similar principle to a keel on a sailboat. However, the unit must be capable of both sinking and floating if recovery is to take place. For this, ballast tanks would be employed. Just like those found on all submarines, ballast tanks would permit air to be pumped into spaces in the structure. This air would displace the water in the tanks and allow the structure to be buoyant.

Finally, the compiled units would be attached to a common circulation system. The connection point would be constructed so as to allow both sides to be sealed when the units are removed. The circulation would act as the spine of the project. Through this axis, all the services to the buildings are provided. They are the primary route of access for residents, as well. Although units may be accessed from the surface level, the lowered circulation route permits residents to move freely, regardless of the submerged status of the project. Along its path, the circulation is connected to public passageways. These paths transect the project and allow the public an opportunity to experience underwater spaces. While the primary goal of this element is an interpretive space, it also permits public pedestrian access across the lengthy site. It is through this experience that the general public may become familiar and increasingly comfortable with the idea of life undersea. This further reinforces the elementary idea of adaptation, in that; these spaces are preparing the public to receive this new adaptive style of living. In the event that sea level rises dramatically, these public spaces would be sealed. In this event, they would be re-tasked to provide open space for submerged residents. These pocket parks would offer opportunities to exercise, walk pets, or experience more open space in a submerged condition.

Overall, the project is designed to be an adaptive accessory to the ocean environment. Its sensitivity to the experiences contained in the undersea world will permit many people the opportunity to have their lives changed by the sea.

4 FINAL THOUGHTS

There is little argument that the sea plays a huge role in our lives on this planet. Therefore, it comes as no surprise that some are expressing interest in its habitation. As our understanding of the sea increases, so does our ability to comprehend and adapt to its changes. If we are to subsist in any changes to this planet, our comprehension and compatibility with the marine environment will be paramount. Projects like these may afford humanity a new platform for understanding and coping with adaptation. Even if changes are not as severe as some may predict, our lives will undoubtedly be enriched for the efforts of facilitating life undersea.

It is my hope that this research will inspire others to further develop the field of undersea architecture. As long as there are people with an undying affinity for the sea, there will be demand for those who wish to better understand it. In closing, I would like to share a caption from Jules Verne's book "20,000 Leagues Under the Sea."   It reminds me of why we yearn to live under the sea, in a way that only the great Captain Nemo can convey:

> "Yes; I love it! The sea is everything. It covers seven tenths of the terrestrial globe. Its breath is pure and healthy. It is an immense desert, where man is never lonely, for he feels life stirring on all sides. The sea is only the embodiment of a supernatural and wonderful existence. It is nothing but love and emotion; it is the 'Living Infinite,' as one of your poets has said. The sea is the vast reservoir of Nature. The globe began with sea, so to speak; and who knows if it will not end with it? In it is supreme tranquility. The sea does not belong to despots. Upon its surface men can still exercise unjust laws, fight, tear one another to pieces, and be carried away with terrestrial horrors. But at thirty feet below its level, their reign ceases, their influence is quenched, and their power disappears. Ah! sir, live--live in the bosom of the waters! There only is independence! There I recognize no masters! There I am free!"

5 BIBLIOGRAPHY

American Concrete Institute. *Ferrocement-Materials and Applications.* Detroit: American Concrete Institute, 1979

Ando, Tadao. "Tadao Ando: Light and Water." New York: The Montacelli Press. 2003

Bainerman, Joel. 2006. "The myths and hype of hydrogen." Middle East , no. 367: 36-38. Academic Search Premier, EBSCOhost (accessed December 4, 2008).

Behar, Michael. "1,200 SQUARE FEET UNDER THE SEA." *Popular Science* 270, no. 1 (January 2007): 64-68. *Academic Search Premier*, EBSCO*host* (accessed September 23, 2008).

Cavuto, Neil. "US Submarines - President Interview." Your World with Neil Cavuto (FOX News) (n.d.).. Newspaper Source, EBSCOhost (accessed September 23, 2008).

Cheston, T. Stephen and David L. Winter ed. *Human Factors of Outer Space Production.* AAAS Selected Symposia Series 50. Boulder: Westview Press, 1980

Chen, Ping, and Min Zhu. 2008. "Recent progress in hydrogen storage." Materials Today 11, no. 12: 36-43. Academic Search Premier, EBSCOhost (accessed December 4, 2008).

Companhia Da Energia Oceanic, S.A. 2008. "World's First Commercial Wave Power Project Goes Live: Babcock & Brown, EDP, and Efacec Join Forces in the Development of Wave Energy." http://www.pelamiswave.com/news.php?id=26 (accessed December 4, 2008)

Cousteau, Jacques-Yves and Fredrick Dumas. *The Silent World*. London: H. Hamilton, 1953.

Daniel, James I. and Surendra Shah, eds. *Fiber Reinforced Concrete: Developments and Innovations*. Detroit: American Concrete Institute, 1994

Friend, Tim. "Astronauts Train in NASA's Deep Space Brine." *USA Today* May 15, 2002.

Gawel, Richard. 2005. "Offshore Power Generation Making Waves." *Electronic Design* 53, no. 6: 26-26. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).

Gengler, Amanda. "Sleep With the Fishes." *FSB: Fortune Small Business* 14, no. 10 (December 2004): 67-70. Bu*siness Source Premier*, EBSCO*host* (accessed September 23, 2008)

Godson, Lloyd, "The Biosub Project." http://www.biosub.com.au (accessed March 01, 2007)

Haux, Gerhard, Jörg Haas, and Anthony Lovell Smith. 1982. *Subsea manned engineering*. Carson, Calif: Best Pub. Co.

Heppenheimer, T.A. *Colonies in Space*. Harrisberg: Stackpole Books, 1977

Holzman, David C. 2007. "Blue Power: Turning Tides into Electricity." *Environmental Health Perspectives* 115, no. 12: A590-A593. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).

Hussain, Farooq. *Living Underwater*. London: Studio Vista, 1970.

Kizis, Sarah. “The Daring Plan to Create Fish Men.” *Writing* 22, No.2 (October 1999): 12

Klaus, Oliver. "Twenty leagues under the sea." *MEED: Middle East Economic Digest* 47, no. 37 (September 12, 2003): 28. *Business Source Premier*, EBSCO*host* (accessed September 23, 2008).

Lang, Jon T. ed. *Designing for Human Behavior: Architecture and the Behavioral Sciences*. Community Development Series, v.6. Dowden, Hutchinson, & Ross, 1974

Marine Technology Society. *Man’s Extension into the Sea*. Transactions of the Joint Symposium. Washington D.C.: Marine Technology Society, 1966

Maruyama, Magoroh. “Aesthetics and the Environment in Outer Space,

Mazria, Edward and Kristina Kirshner “Nation Under Seige: Sea Level Rise at Our Doorstep.” (September 2007) 2030, Inc. / Architecture 2030 www.architecture2030.org (accessed October 13, 2008)

"Proposed Hotel Would Make Jacques Cousteau Proud." *Meeting News* 29, no. 4 (March 21, 2005): 6-6. *Business Source Premier*, EBSCO*host* (accessed September 23, 2008).

Pauley, Stephen M. “Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue,” Medical Hypotheses Vol. 63, Issue 4 (2004), http://www.sciencedirect.com/science/journal/03069877 (accessed December 3, 2008)

Subterranean and Underwater Communities.” *Futures* 16, No.2 (April, 1984): 148-62.

Miller, James W. and Ian G. Koblick. *Living and Working in the Sea*. New York: Van Nostrand Reinhold. 1984.

Mooring Jr., Frank. “Deep Space.” *Aviation Week & Space Technology* 161, No.2 (July 2004)

Moore, Charles. “Water and Architecture.” New York: Harry N. Abrams, 1994.

National Oceanographic and Atmospheric Administration. “Aquarius Underwater Laboratory: America’s “Inner Space” Station.” NOAA Ocean Explorer (June 14, 2007)http://www.oceanexplorer.noaa.gov/technology/diving/aquarius/aquarius.html

Rapoport, Julie, Corina-Maria Aldea, Surendra P. Shah, Bruce Ankenman, and Alan F. Karr. “Permeability of Cracked Steel Fiber-Reinforced Concrete,” National Institute of Statistical Sciences Technical Report Number 115 (January 2001).http://www.niss.org/technicalreports/tr115.pdf (accessed December 1, 2008).

Ross, Frank Jr. Undersea Vehicles and Habitats: The Peaceful Uses of the Ocean. New York: Thomas Y. Crowell, 1970

Simbeck, D.R. 2004. "*CO2 capture and storage—the essential bridge to the hydrogen economy.*" Energy 29, no. 9/10: 1633-1641*. Academic Search Premier, EBSCOhost* (accessed December 4, 2008).

Stachiw, Jerry D. 1982. *Acrylic plastic viewports: ocean engineering and other hyperbaric applications*. New York: M. Dekker.

Savage, Marshall. *The Millennial Project*. Denver: Empyrean Publishing, 1992.

U.S. Department of the Navy. *U.S. Navy Diving Manual*. Washington D.C.: Government Printing Office, 1970, NAVSHIPS 0994-001-9010.

U.S. Deparment of Commerce. *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*, President's Panel for Ocean Exploration, 2001

Zenta Kato, Koichi Izumiya, Naokazu Kumagai, and Koji Hashimoto. 2009. "Energy-saving seawater electrolysis for hydrogen production." *Journal of Solid State Electrochemistry* 13, no. 2: 219-224. *Academic Search Premier*, EBSCO*host* (accessed December 4, 2008).

Zumthor, Peter. *Atmospheres*. Basel: Birkhauser, 2006.

6 Image Credits

Error! Reference source not found.: Climate Change Prediction Program http://www.csm.ornl.gov/chammp/ accessed April 02, 2009

2.1-2 Levees overtopping, September 2008: Steven Morton/ Getty Images http://architecture.about.com/od/damsresevoirs/ss/floodcontrol.htm accessed May 05, 2009

2.1-1 Hawaiian Green Sea Turtle: Chad Henderson Original Photography

2.3-1 Freediving Ascent: Chad Henderson Original Photograph

2.3-1 Simple Diving Bell: Hussain, Farooq. *Living Underwater*. London: Studio Vista, 1970. Pg. 30

3.2-1 Aquarius undersea laboratory: MSNBC http://www.msnbc.msn.com/id/20837437/ Accessed April 02, 2009

3.1-1 Early Diving Bell: Miller, James W. and Ian G. Koblick. *Living and Working in the Sea*. New York: Van Nostrand Reinhold. 1984. Pg 4

3.2-1 Launching Man in the Sea I: Miller, James W. and Ian G. Koblick. *Living and Working in the Sea*. New York: Van Nostrand Reinhold. 1984. Pg. 29

3.2-2 Observing Marine life in Sealab II: Miller, James W. and Ian G. Koblick. *Living and Working in the Sea*. New York: Van Nostrand Reinhold. 1984. Pg. 156

4.4-1 View Inside Ithaa: Trifter-travel website http://www.trifter.com/Practical-Travel/Luxury-Travel/Unusual-Eating-Places-Underwater-Restaurants.366251 **accessed April 02, 2009**

4.5-1 Huvafen Fushi Spa: Maldives resorts http://www.huvafenfushi.com/spa_photo.php accessed April 02, 2009

4.5-2 Underwater Treatment Room: Maldives resorts http://www.huvafenfushi.com/spa_photo.php accessed April 02, 2009

4.5-3 Lighting Effects Underwater: Maldives resorts http://www.huvafenfushi.com/spa_photo.php accessed April 02, 2009

4.4-1 View Inside Ithaa: MJ Murphy Ltd. http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx Accessed 02,2009

4.4-2 Ithaa Being Lowered into the Water: MJ Murphy Ltd. http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx Accessed 02,2009

4.3-2 Restaurant Interior: Red Sea Star http://www.redseastar.com/pictures-en.php Accessed April 02, 2009

4.3-1 Restaurant Exterior: Red Sea Star http://www.redseastar.com/pictures-en.php Accessed April 02, 2009

4.6-1 Habitat Map: Jules' Undersea Lodge http://www.jul.com/ Accessed April 02, 2009

4.6-2Lodge Dining Hall: Jules' Undersea Lodge http://www.jul.com/ Accessed April 02, 2009

4.6-1 Hydropolis: Dubai Information Site http://www.dubai-information-site.com/hydropolis.html Accessed April 02, 2009

5.1-2 compound Layout: Newagen Seaside Inn http://www.boothbayharborblog.com/newagen_seaside_inn/2008/03/the-most-amazin.html Accessed 02, 2009

6.1-1 Cabin Interior: Newagen Seaside Inn http://www.boothbayharborblog.com/newagen_seaside_inn/2008/03/the-most-amazin.html Accessed 02, 2009

6.2-1 The Hydropolis Resort: Dubai Information Site http://www.dubai-information-site.com/hydropolis.html Accessed April 02, 2009

2.1-1 Artificial Reef Off Oahu: Chad Henderson Original Photography

2.2-1 Anchored Habitat: Miller, James W. and Ian G. Koblick. *Living and Working in The Sea*. New York: Van Nostrand Reinhold. 1984. Pg 348

2.2-2 Artist's Sketch of a Habitat on Pilings Miller, James W. and Ian G. Koblick. *Living and Working in The Sea*. New York: Van Nostrand Reinhold. 1984. Pg 409

4.2-1 Ferrocement Boat Under Construction: Bolton School Boy's Division, "plastering Process" http://www.boltonschool.org/SeniorBoys/ExtraCurricular/MillenniumKetch/Plastering/ Accessed may, 05 2009.

6.1-1 Pelamis Wave Energy Converter: Pelamis Wave Evergy http://www.pelamiswave.com/galleryimages.php?offset=10, Accessed May, 05 2009.

3.1-1 Kelp: THE SPA FLYER http://www.spaflyer.com/2008/01/spa-at-home-fri.html Accessed 02, 2009

2.3-1THE DESIGN OF CITIES COMPETITION ENTRY BY EISENMANN: From the book "Tracing Eisenmann"

6.2-1 Water Temple by Tadao Ando in Awaji Island, japan: from the book "Tadao Ando: Light and Water" p 120